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Acquisition Research:
Creating Synergy for Informed Change

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Preface & Acknowledgements

Welcome to our Tenth Annual Acquisition Research Symposium! We regret that this year it will be a “paper only” event. The double whammy of sequestration and a continuing resolution, with the attendant restrictions on travel and conferences, created too much uncertainty to properly stage the event. We will miss the dialogue with our acquisition colleagues and the opportunity for all our researchers to present their work. However, we intend to simulate the symposium as best we can, and these *Proceedings* present an opportunity for the papers to be published just as if they had been delivered. In any case, we will have a rich store of papers to draw from for next year’s event scheduled for May 14–15, 2014!

Despite these temporary setbacks, our Acquisition Research Program (ARP) here at the Naval Postgraduate School (NPS) continues at a normal pace. Since the ARP’s founding in 2003, over 1,200 original research reports have been added to the acquisition body of knowledge. We continue to add to that library, located online at www.acquisitionresearch.net, at a rate of roughly 140 reports per year. This activity has engaged researchers at over 70 universities and other institutions, greatly enhancing the diversity of thought brought to bear on the business activities of the DoD.

We generate this level of activity in three ways. First, we solicit research topics from academia and other institutions through an annual Broad Agency Announcement, sponsored by the USD(AT&L). Second, we issue an annual internal call for proposals to seek NPS faculty research supporting the interests of our program sponsors. Finally, we serve as a “broker” to market specific research topics identified by our sponsors to NPS graduate students. This three-pronged approach provides for a rich and broad diversity of scholarly rigor mixed with a good blend of practitioner experience in the field of acquisition. We are grateful to those of you who have contributed to our research program in the past and encourage your future participation.

Unfortunately, what will be missing this year is the active participation and networking that has been the hallmark of previous symposia. By purposely limiting attendance to 350 people, we encourage just that. This forum remains unique in its effort to bring scholars and practitioners together around acquisition research that is both relevant in application and rigorous in method. It provides the opportunity to interact with many top DoD acquisition officials and acquisition researchers. We encourage dialogue both in the formal panel sessions and in the many opportunities we make available at meals, breaks, and the day-ending socials. Many of our researchers use these occasions to establish new teaming arrangements for future research work. Despite the fact that we will not be gathered together to reap the above-listed benefits, the ARP will endeavor to stimulate this dialogue through various means throughout the year as we interact with our researchers and DoD officials.

Affordability remains a major focus in the DoD acquisition world and will no doubt get even more attention as the sequestration outcomes unfold. It is a central tenet of the DoD’s Better Buying Power initiatives, which continue to evolve as the DoD finds which of them work and which do not. This suggests that research with a focus on affordability will be of great interest to the DoD leadership in the year to come. Whether you’re a practitioner or scholar, we invite you to participate in that research.

We gratefully acknowledge the ongoing support and leadership of our sponsors, whose foresight and vision have assured the continuing success of the ARP:

- Office of the Under Secretary of Defense (Acquisition, Technology, & Logistics)
- Director, Acquisition Career Management, ASN (RD&A)
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Acquisition Management

Naval Ship Maintenance: An Analysis of the Dutch Shipbuilding Industry Using the Knowledge Value Added, Systems Dynamics, and Integrated Risk Management Methodologies

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Time as an Independent Variable: A Tool to Drive Cost Out of and Efficiency Into Major Acquisition Programs

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National Defense Business Institute, University of Tennessee

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Naval Ship Maintenance: An Analysis of the Dutch Shipbuilding Industry Using the Knowledge Value Added, Systems Dynamics, and Integrated Risk Management Methodologies

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Abstract

Initiatives to reduce ship maintenance costs have not yet realized the normal cost-reduction learning curve improvements. One explanation is the lack of recommended technologies. Damen, a Dutch shipbuilding and service firm, has incorporated similar technologies and is developing others to improve its operations. This research collected data on Dutch ship maintenance operations and used it to build three types of computer simulation models of ship maintenance and technology adoption. Results were compared with previously developed modeling results of U.S. Navy ship maintenance and technology adoption. Adopting 3D PDF alone improves ROI significantly more than adopting a logistics package alone, and adding both technologies improves ROI more than adding either technology alone. Adoption of the technologies would provide cost benefits far in excess of not using the technologies, and there were marginal benefits in sequentially implementing the technologies over immediately implementing them. Potential benefits of using the technologies are very high in both cases. Implications for acquisition practice include the need for careful analysis and selection from among a variety of available information technologies and the

recommendation for a phased development and implementation approach to manage uncertainty.

Introduction

The current cost-constrained environment within the federal government and the DoD requires a defensible approach to cost reductions without compromising the capability of core defense processes and platforms. Due to this environment, defense leaders today must maintain and modernize the U.S. armed forces to retain technological superiority while simultaneously balancing defense budget cost constraints and extensive military operational commitments. At the same time, defense leaders must navigate a complex information technology (IT) acquisition process. Maintenance programs play a critical role in meeting these DoD objectives. One such core process that is central to U.S. naval operations is the ship maintenance process. This process alone accounts for billions of dollars in the U.S. Navy's annual budget. There have been a series of initiatives designed to reduce the cost of this core process, including ship maintenance. SHIPMAIN, and its derivatives, was one of the initiatives designed to improve ship maintenance performance within the Navy by standardizing processes in order to take advantage of learning curve cost savings.

However, these process improvement initiatives have not yet realized the normal cost-reduction learning curve improvements for common maintenance items for a series of common platform ships. One explanation is that the initial instantiation of SHIPMAIN did not include two recommended technologies, three-dimensional laser scanning technology (3D LST) and collaborative product life-cycle management (CPLM), that were deemed necessary by the creator of SHIPMAIN for ensuring the success of the new standardized approach (i.e., normal learning curve cost savings). Previous research (Ford, Housel, & Mun, 2011) indicates that adding these technologies may help SHIPMAIN, or its derivatives, to capture the potential savings. But the technologies have not been implemented to date in the ship maintenance processes.

However, Damen, a large shipbuilding and service firm has incorporated similar technologies and is developing others to improve its operations. In addition, the Royal Dutch Navy (RDN) performs all of its own ship maintenance in a single yard and operation. In the current study, the potential benefits of similar technologies are extrapolated and compared with similar projections for U.S. Navy ship maintenance processes. These organizations provide a source of relatively reliable data on operations that are comparable to those performed by the U.S. Navy.

Problem Description

Previous research on the potential use of 3D LST and CPLM technology in U.S. Navy ship maintenance (e.g., Komoroski, 2005; Ford, Housel, & Mun, 2011) estimated the impacts on processes due to technology adoption. Changes such as reengineering ship maintenance processes, the sizes of reductions in cycle times, and workforce requirements are examples of model portions that required modelers to make assumptions about the potential impacts of these technologies in modeling projected results. While the previous work has provided defensible estimates of potential improvements (in returns on investment, ROI) and cost savings, the validity and usefulness of these models has been limited by the lack of comparative data on ship maintenance processes and technology investments, and of their potential impacts on performance. Therefore, the acquisition of data on Dutch naval fleet maintenance processes and the comparison of those data with previous U.S. Navy results were critical steps in improving U.S. naval technology acquisition decision-making, in particular with regard to ship maintenance.

To be valuable, the data source or sources for this work had to have several critical similarities with U.S. naval ship maintenance processes. The data source had to consider technological innovation and the adoption of advanced technologies to be an important part of its naval maintenance acquisition strategy. The data source or sources had to be large enough to support continuous ship maintenance operations because the intermittent stopping and restarting of operations would not be consistent with important assumptions of the modeling approach. Finally, the data source had to be accessible, willing to share the data, and willing to allow us to obtain the new data required for our modeling approach. These and other criteria limited the potential pool of sources to nations or large industrial ship maintenance organizations that were on good terms with the United States, advanced enough in their operations to compare with those of the U.S. Navy, progressive enough in their strategies to include continuous technology adoption, and willing to share data and information that is often considered essential for national security or competitive advantage. Damen Industries and the RDN met most of these criteria and were willing to meet our requirements for data acquisition and sharing.

The current work addresses the following questions:

- How are the Dutch using and preparing to adopt advanced technologies, such as 3D LST and CPLM, in shipbuilding and maintenance?
- What are the potential changes in ROIs provided by the adoption of these advanced technologies?
- How do those potential returns compare with projected estimates of returns on technology adoption of 3D LST and CPLM in the U.S. Navy?

Research Methodology and Background[1]

The traditional ROI equation is typically expressed as (revenue – investment)/investment, which represents the productivity ratio of output (i.e., revenue in ROI ÷ input or investment cost in ROI). Accomplishing this analysis in a nonprofit environment presents challenges because there is no actual revenue generated. Cost savings from reductions in manpower requirements (i.e., time allocated to employee workload for various tasks) is available to provide the impact on the denominator of the ship maintenance efforts. The knowledge value added (KVA) methodology (Housel & Kanevsky, 1995) also allows for generation of a quantifiable surrogate for revenue in the form of common units of output described in terms of units of learning time. Specifically, the KVA methodology allowed the study team to quantify the knowledge embedded in the new processes to use in generating common units of output estimates. The KVA analysis provided the basic ROI estimates critical in forecasting the future value of various automation options.

The system dynamics methodology was used to model the impacts of automation on operations. System dynamics applies a control theory perspective to the design and management of complex human systems. System dynamics combines servo-mechanism thinking with computer simulation to create insights about the development and operation of these systems. Forrester (1961) developed the methodology's philosophy, and Sterman (2000) specified the modeling process with examples and described numerous applications. System dynamics is used to build causal-based (versus correlation-based) models that reflect the components and interactions that drive behavior and performance. The methodology has been used extensively to explain, design, manage, and, thereby, improve

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[1] See Ford, Housel, and Mun (2012) for a more detailed description of the research methodologies applied.

the performance of many types of systems, including development projects. The methodology's ability to model many diverse system components (e.g., work, people, money, value), processes (e.g., design, technology development, production, operations, quality assurance), and managerial decision-making and actions (e.g., forecasting, resource allocation) makes system dynamics useful for modeling and investigating military operations, the design of materiel, and acquisition.

The integrated risk management (IRM) framework and supporting toolset was used to optimize the portfolio over time. IRM is an eight-step, quantitative, software-based modeling approach for the objective quantification of risk (cost, schedule, technical), flexibility, strategy, and decision analysis. The method can be applied to program management, resource portfolio allocation, return on investment to the military (maximizing expected military value and objective value quantification of nonrevenue government projects), analysis of alternatives or strategic flexibility options, capability analysis, prediction modeling, and general decision analytics. The method and toolset provide the ability to consider hundreds of alternatives with budget and schedule uncertainty and provide ways to help the decision-maker maximize capability and readiness at the lowest cost. This methodology is particularly amenable to resource reallocation and has been taught and applied by the authors for the past 10 years at over 100 multinational corporations and over 30 projects at the U.S. Department of Defense (DoD).

The research team collected data on Dutch ship operations as described in the section titled Data Collection Methods and used it to build three types of computer simulation models of ship maintenance and technology adoption: KVA models of return on technology investments in those operations, system dynamics models (SD) of ship maintenance operations, and IRM models of implementation plans for technology adoption. The results were then analyzed and compared with previously developed modeling results of U.S. Navy ship maintenance and technology adoption.

Data Collection Methods

Data on the practices of Dutch industry and naval ship maintenance proved very difficult and time consuming to obtain. Initial contact with Dutch industry participants and ship maintenance technology providers developed slowly over several months into relationships that eventually led to data collection opportunities. Several sources of data were utilized, including a Dutch shipbuilder (Damen) and the RDN. Data on the use of technology in Dutch fleet maintenance was collected by two primary methods: (1) in-person interviews and meetings with managers of the leading corporation in the Dutch shipbuilding industry (Damen) and with officers and civilian employees of the RDN, and (2) tours of three Dutch shipbuilding and maintenance facilities.

In-person interviews and meetings with managers at Damen and with officers and a civilian employee of the RDN occurred during a data collection trip by one of the research team members (Ford) to the Netherlands in June 2012, as did the tours of Dutch ship building and maintenance facilities. Meetings, semi-structured interviews, and extended discussions were held with six managers of Damen Industries and the RDN in three locations over three days. At these meetings, Damen managers made presentations on Damen's operations, uses of technologies, investigations of specific technologies for potential development and adoption (including 3D LST and CPLM software), Integrated Logistics System (ILS), and information technology products under development for use in ship maintenance.[2] Separately, a meeting and semi-structured interview was conducted with

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[2] Copies of these presentations were requested, but not provided. Data collection results are based on notes taken by the investigator during the meetings, interviews, and tours of facilities.

the two RDN officers responsible for ship maintenance at the RDN shipyard at Nieuwe Haven in Den Helder. Tours of the RDN fleet maintenance facility in Nieuwe Haven and two Damen shipyards were provided during the data collection trip.

Data Collection Results

Damen's Use of Technology

The Damen Shipyards Group (www.damen.nl/) is a large Dutch shipbuilding firm with worldwide operations (11 shipyards with five outside The Netherlands). The firm was started in 1922 by Jan and Rien Damen. The firm grew substantially after Kommer Damen (the current owner) bought it in 1969 and introduced modular and standardized shipbuilding to the industry. The firm now employs over 6,000 people and builds an average of 150 vessels per year. The firm obtained Damen Schelde in 2000, which focuses exclusively on naval ship design, building, and maintenance. Damen Schelde manufactures an average of one to two ships per year, employs about 550 people, and performs about €210 million per year. Damen Schelde acts as the prime contractor and integrator on its shipbuilding projects, utilizing many subcontractors. Although Damen Schelde provides ship maintenance services to its international (i.e., not Dutch) customers, it does not provide any ship maintenance services for the RDN.

Damen Schelde has used an ILS since 2002 to manage the shipbuilding process from project initiation through the development of a logistics plan for customers. The ILS is the plan for the development of a ship and includes ship design; production; quality assurance, quality control (QAQC); training of ship operators; and coordination with customers. The ILS does not include service contracts or life-cycle costs due to the difficulty of forecasting those costs. The focus of the ILS is to provide maximum ship operational availability, reliability, and maintainability. It does this partially by using a single point of contact within Damen throughout the project who manages an interdisciplinary team (e.g., engineering, work preparation, procurement, service). Damen Schelde currently uses a variety of information technologies to facilitate their ILS approach to shipbuilding and is constantly investigating new technologies that may improve its design and manufacturing. Of particular relevance to the current work, Damen Schelde uses four separate software products to manage its shipbuilding: an advanced three-dimensional CADD program for design, a CPLM product as a database for ship components, an Enterprise Resource Planning (ERP) system, and a software tool for scheduling. The latter three of these systems are connected to users with a project information portal developed by Damen Schelde. The informant reported that Damen developed the portal because the CPLM product did not include adequate user interfaces.

Damen Schelde has investigated and is currently investigating other technologies for potential adoption. Four technologies were described and discussed:

1. 3D LST: This technology was investigated but was assessed to currently be too immature for adoption by Damen Schelde. The investigation included a discussion of the current use of the technology in the automobile industry, as well as its potential use to scan engine rooms and for floor flattening. The use of 360-degree photography (often used in conjunction with 3D LST) was considered by Damen Schelde as a potential tool for training (see Komoroski, 2005, for more details on 3D LST).
2. 3D PDF files: Three-dimensional animated "movies" of shipbuilding can be created in a PDF format (by Adobe Acrobat®) and sent to shipyards for use in the field by craftsmen who view the file on an electronic reader (e.g., an iPad®). The files would replace flat drawings for use in construction. The file

visually communicates the sequence of building (or maintenance) operations and components, and operations can have notes attached to them that provide additional information (e.g., part numbers or warnings of special issues). The ability to animate these files allows engineers to visually show craftsmen sequences of operations, routes of access and egress for line replaceable units (LRU[3]), and other information that is difficult or impossible to show with traditional, static, two-dimensional drawings. The use of this technology shifts the understanding of the design intention from the designers (in the Netherlands) to the shipbuilding yard (typically in other countries around the world). The use of visual information (the animation of steps) is expected to greatly improve communication across languages since many of the craftsmen in Damen's shipyards do not read English well. Damen considers improvements in information content communicated to be the primary benefit of this system (versus cost savings). Damen Schelde is very optimistic about the potential for this technology to improve its operations and is actively working on developing it (e.g., selecting software, addressing the importing of the 3D design drawings). Generating the animated files and adding the building steps to the design files is expected to be relatively easy once the system has been developed.

3. SIGMA Shipbuilding Strategy: This is a standardized process for creating a ship that spans from design through materials procurement, production, and testing of a ship. The key feature of the strategy is the use of modular ship sizes and systems that can be easily adapted to specific customer needs. For example, Damen Schelde has disaggregated an entire ship into five standardized modules (e.g., fore, midship, aft) with major systems located in specific sections. Each module is considered a subproject. As an example of an advantage provided by the strategy, the modules and their interfaces are designed such that the ship can be made longer by adding an additional midsection.[4]
4. Radio Frequency Identification (RFID): This established technology is being considered for use to improve Damen's supply chain management. Primary benefits are believed to be improved value of information and a reduction in the duration for getting information into Damen databases (e.g., warehouse contents, components on specific ships). Both passive and active tags are being considered.

Damen Services also develops advanced technologies for use by Damen Enterprises. Damen Services focuses on providing ongoing maintenance parts and services to Damen customers after a ship has been designed, built, and delivered, but also provides other services such as civil works (e.g., wharves and storage facilities).

The Maintenance and Spares department maintains information on ship configuration (using an ERP system), parts inventories, spare parts packages, and maintenance management systems. It also provides information technology support for Damen. It is developing a web portal for clients that will allow clients access to Damen-held data on each of the customer's ships down to the individual component level. This will

[3] *Line replaceable unit* is a commonly used term in manufactured devices for any modular component that is designed to be interchangeable.
[4] This portion of the SIGMA strategy applies the Boeing strategy for the design and production of the 737 that has different lengths to shipbuilding.

partially be accomplished with a work breakdown system (WBS) that disaggregates a ship or system into product parts (e.g., engine, bilge pump) and a functional breakdown system that disaggregates the ship into functions (e.g., port propulsion) that are met with a product part (in the WBS) and have an associated maintenance schedule, which includes monitoring measurements and frequency, parts documentation, and so forth. The WBS has three levels: subsystems (e.g., propulsion, hoisting), with a typical ship having 20–70 subsystems; Level 2 parts (e.g., pump, shaft), with about 1,000 per ship; and Level 3 parts (e.g., bolt, flange), with 70,000–80,000 per ship.

This system will be linked with an online parts ordering portal so that customers can order parts from Damen (similar to Amazon's online selling of books, etc.). Damen Services plans to use the information (e.g., the frequency orders for specific components) captured through this system to develop maintenance optimization information. Damen Services envisions three types of maintenance: corrective maintenance (after the component needs work), preventative maintenance (based on forecasts of maintenance needs), and condition-based maintenance (based on actual conditions of components). Condition-based maintenance is an optimized version of preventative-based maintenance that is currently under development. It requires sensors to collect data on component conditions that will be used to generate condition assessments.

Royal Dutch Navy Fleet Maintenance

Data collection directly from the RDN was particularly valuable for at least two reasons. First, as the navy of a sovereign country with objectives that are similar to those of the United States, the objectives and issues of the RDN are more likely to match those of the U.S. Navy than those of some other nations. Data collection supported this assumption. For example, technology leadership, interoperability, and reliability in meeting operational needs are paramount to the RDN, and the RDN has recently experienced, and expects to continue to experience, reductions in budgets just as is the case with the U.S. Navy. The Dutch navy continues to face budget cuts and increasing technology needs, is currently in reorganization to reduce total workforce (internal to the navy and civilian naval workforce) by 20%, and is transferring from legacy information systems to an integrated ERP system for maintenance operations. Also, the RDN performs all of the maintenance on its fleet, thereby making it the primary data source concerning RDN fleet maintenance process performance.

The interviews with the two RDN officers in the Naval Maintenance and Service Agency provided a general introduction to the issues faced by the Dutch navy in building and maintaining its fleet. The RDN addresses its challenges by means similar to those used by the U.S. Navy, such as waiting for technology to mature (technology readiness level [TRL] ≥ 7 before adoption) and incremental capability increases based on budgets. Noticeably different, both the RDN and Damen described the critical role, and standard Dutch practice, of adjusting requirements to meet budgets in shipbuilding. The RDN is facing increasing pressure to control life-cycle costs in its fleet, which are largely driven by personnel and fuel. This has led it to approve significantly stricter operations manning requirements for ship design (i.e., lower maximum shipboard personnel), which has driven Damen to increase the use of automation in its ship designs.

The primary informant on RDN fleet maintenance operations provided a diagram of those operations (see Figure 1) and a written description of each of the steps identified in the diagram.

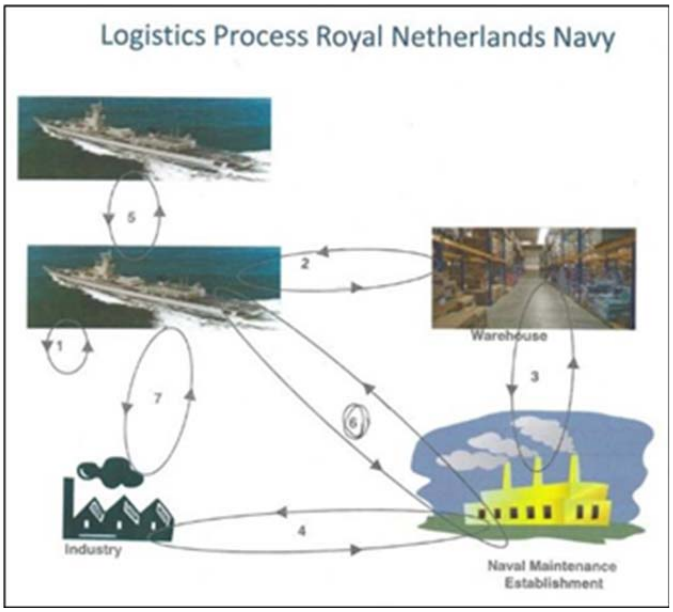

Figure 1. Diagram of Royal Dutch Navy Fleet Maintenance Processes
(P. Kense, personal communication, June 21, 2012)

The process steps shown in Figure 1 were described in writing by the informant with the following list.[5] In the list, the abbreviation *LRU* stands for *line replaceable unit*, a commonly used term in the area of manufactured devices for any modular component that is designed to be interchangeable.

Logistic Process Royal Netherlands Navy

1. In case LRU fails the on-board personnel will replace this LRU by a spare (on-board; OLM qualification required).
2. The defect LRU will be send to the warehouse, and a “new” LRU will be send to the ship.
3. The defect LRU will be send to the Naval Maintenance Establishment (NME) for repair. After the LRU is repaired it will be send to the warehouse again “as good as new” (DLM qualification required).
4. If the NME needs parts to repair an LRU, the parts will be extracted from the industry, when the NME is not able to repair this LRU, it can be send to the manufacturer. Also, manpower can be hired to fix problems.
5. If spare is not available, sometimes it will be cannibalized from another ship.
6. If the on-board personnel is not able to fix the problem by themselves (due to the complexity of the failure) assistance from the NME is needed (ILM qualification required).
7. If the problem is too complex for the NME also, the industry can be hired to solve this problem.

The following seven process steps were elaborated on by the informant (the abbreviations *DLM*, *OLM*, and *ILM* refer to Dutch terms for training levels):

[5] The process step descriptions have been transcribed exactly as provided in English by the RDN, including uncommon English grammar and spelling.

Step 1: Performed onboard, for example to provide operational maintenance of weapons systems

Step 2: Purely a transit operation that requires only a truck driver (if ship is in port)

Step 4: Requires DLM level of training

Step 5: Requires OLM level of training

Step 6: Requires ILM level of training (= LTS + MTS + 10 – 25 days of training)

Step 7: Requires DLM level of training

Fleet maintenance for the RDN requires, at a minimum, completion of education at a Lower Technical School (LTS) and a Middle/Intermediate Technical School (MTS). The LTS is typically attended between ages 12–16, and the MTS is typically attended between ages 16–21. After completion of LTS and MTS, future RDN ship fleet maintenance personnel must complete at least one of three other forms of training.

System Dynamics Model Structure

The system dynamics model simulates the movement of LRU among the various locations where they are used, stored, or repaired. Each flow of LRUs between two stocks represents the processing rate of one of the process steps in a KVA model. A simplified diagram of the stocks and flows of the model are shown in Figure 2. Boxes represent stocks, or accumulations of LRU. Each stock in Figure 2 represents a location in Figure 1, plus on-board LRU storage as a separate LRU accumulation. Arrows with valve symbols in Figure 2 represent the movement of LRUs between stocks. Numbers in parentheses in the titles of flows represent the process steps shown in Figure 1 (ovals with arrows) and the KVA model process steps (described later).

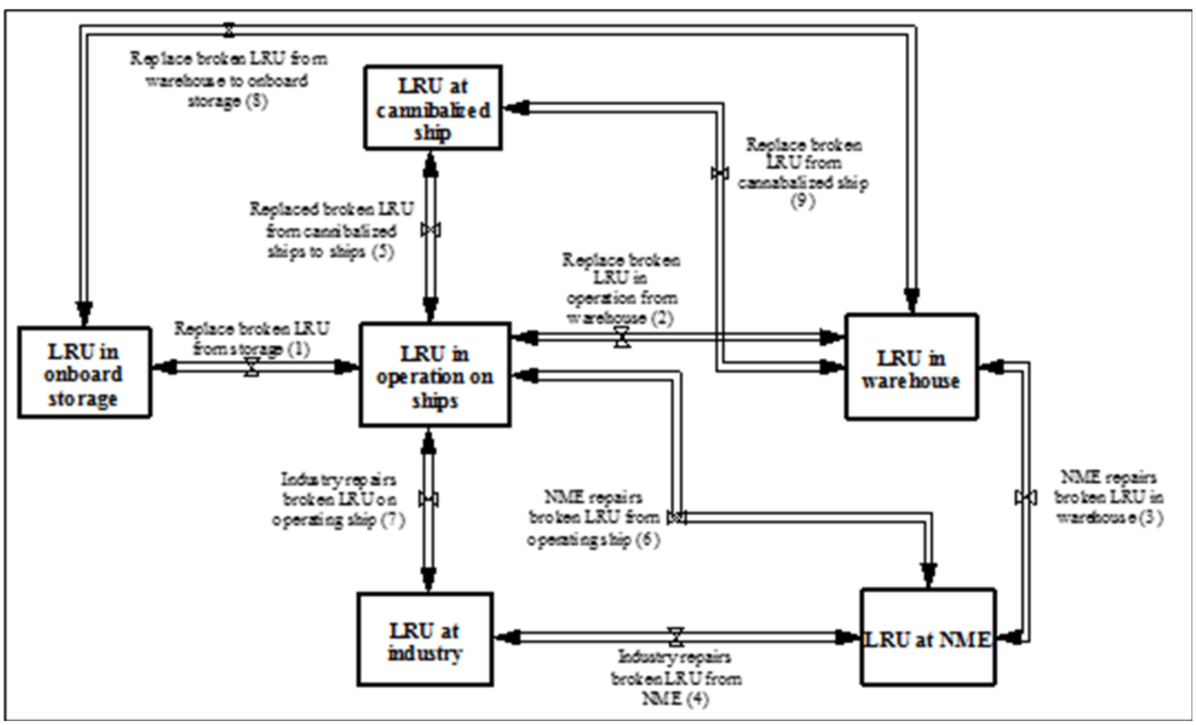

Figure 2. Royal Dutch Navy Ship Maintenance: Stocks and Flows of the System Dynamics Model

The sizes of the flows in the system dynamics model describe the rate of movement of LRUs among the stocks. Therefore, the simulated flows in the system dynamics model become direct inputs to the "times processed per year" portion of the KVA models. Flow rates were modeled to reflect the sequence of processes in operations. For example, in normal operations, the replacement of a broken LRU in an operating ship with one from the ship's on-board storage ("Replace broken LRU from storage [1]" on the left of Figure 2) would be followed by the broken LRU in storage being replaced by an operational LRU from the warehouse ("Replace broken LRU from warehouse on onboard storage [8]" at the top in Figure 2). This replacement would be followed by the broken LRU being sent to the NME where it would be repaired and returned to the warehouse ("NME repairs broken LRU in warehouse [3]" on the right in Figure 2). These precedencies are modeled by having the downstream process equal to its preceding process step with a delay that reflects the transit and subsequent processing time. Some flows (e.g., "NME repairs broken LRU from warehouse [3]") are aggregations of multiple upstream flows. Core flows are based on the mean time between failure of LRUs and the fraction of failures addressed with each process.

The system dynamics model was calibrated to reflect RDN ship maintenance (see Ford, Housel, & Mun, 2012, for details).

Knowledge Value Added Models to the Royal Dutch Navy Ship Maintenance

Four KVA models were built based on the RDN ship maintenance processes (see Ford, Housel, & Dillard, 2010, for details and examples of KVA modeling):

1. Baseline RDN ship maintenance processes
2. Baseline RDN ship maintenance processes changed to reflect the adoption and use of a logistics package from an integrated CPLM system such as was investigated by Damen
3. Baseline RDN ship maintenance processes changed to reflect the adoption and use of 3D PDF modeling managed with a CPLM system as planned by Damen
4. Baseline RDN ship maintenance processes changed to reflect the adoption and use of a logistics package and 3D PDF modeling managed by an integrated CPLM system

Model Simulations and Results

The system dynamics model was simulated to represent the four technology adoption scenarios described in the previous section. The output of each system dynamics model simulation was used as input to a KVA model. Those KVA models were then used to estimate the ROI of each process in each of the four scenarios and the cumulative ROI for each scenario. The results based on the models and their calibrations are shown in Table 1.

Table 1. Knowledge Value Added Model Results

	Process Description	Return On Investment (ROI) Baseline	Add Logistics	Add 3D PDF	Add Logistics & 3D PDF
1	Replace LRU with on-board spare	90%	261%	501%	464%
2	Replace operating LRU with warehouse spare	90%	151%	621%	1027%
3	NME repairs warehouse LRU and returns it to warehouse	8%	65%	95%	236%
4	Manufacturer repairs LRU for NME & it returns to warehouse	31%	88%	168%	168%
5	Replace on-board LRU with LRU cannibalized from another ship	90%	151%	621%	1027%
6	NME repairs on-board LRU and returns it to ship	265%	10%	99%	192%
7	Industry repairs on-board LRU and returns it to ship	34%	178%	135%	318%
8	Replace on-board storage LRU with warehouse spare (transit only)	301%	759%	759%	759%
9	Replace cannabalized LRU with warehouse spare (transit only)	140%	329%	862%	1102%
	TOTAL ALL PROCESSES	35%	77%	135%	274%

Although increased throughput due to reduced processing durations (which increase the ROI numerator) can partially explain differences in the ROI in Table 1, cost reduction (which decreases the ROI denominator) is the primary driver of increases in ROI. For example, Processes 8 and 9 are benefitted by reductions in rework (e.g., errors in transporting LRU) due to the adoption of a logistics package. This reduces the number of transport trips required (the function of these processes), thereby significantly reducing costs and increasing the ROI. In contrast, Processes 3, 4, and 6 are highly skilled processes that are difficult to replace with technology and, therefore, benefit less from technology adoption than other processes. This results in a smaller increase in ROI for these processes.

Analysis of Simulation Model Results

A variance analysis was performed on the KVA model results (Table 1) to evaluate the relative impacts of the adoption of different technologies (Table 2). ROIs for each of the three technology adoption alternatives were compared with the baseline ROIs to estimate improvement due to technologies (see the left three columns of results in Table 2). In addition, the improvement from adopting both technologies over adopting only the 3D PDF technology was estimated (see the right column in Table 2).

Table 2. Variance Analysis of Knowledge Value Added Model Results

	Process Description	Return On Investment (ROI)			
		Add Logistics - Improvement over Baseline	Add 3Dpdf - Improvement over Baseline	Add Logistics & 3Dpdf - Improvement over Baseline	Add Logistics & 3Dpdf - Improvement over adding only 3Dpdf
1	Replace LRU with on-board spare	171%	411%	374%	-38%
2	Replace operating LRU with warehouse spare	61%	532%	937%	406%
3	NME repairs warehouse LRU and returns it to warehouse	57%	87%	227%	140%
4	Manufacturer repairs LRU for NME & it returns to warehouse	57%	138%	138%	0%
5	Replace on-board LRU with LRU cannibalized from another ship	61%	532%	937%	406%
6	NME repairs on-board LRU and returns it to ship	-256%	-166%	-73%	93%
7	Industry repairs on-board LRU and returns it to ship	145%	101%	284%	183%
8	Replace on-board storage LRU with warehouse spare (transit only)	458%	458%	458%	0%
9	Replace cannabalized LRU with warehouse spare (transit only)	189%	721%	962%	240%
	TOTAL ALL PROCESSES	**42%**	**100%**	**239%**	**139%**

Referring to Table 2, adding either or both of the technologies improves overall ship maintenance ROI, as indicated by the positive numbers in the last row of Table 2. Adopting 3D PDF alone improves ROI significantly more than adopting a logistics package alone (100% improvement > 46% improvement), and adding both technologies improves ROI more than adding either technology alone (239% improvement > 42% improvement or 100% improvement), suggesting that there may be synergy between the technologies. This is also supported by the 139% improvement by adding logistics if 3D PDF is already in place (see the lower right result in Table 2).

Adopting the technologies does not impact the ROI of individual processes equally. Among the seven core processes (1–7), adding only a logistics package (see the left column of results in Table 2) increases the "Replace LRU with on-board spare" (Process 1) most, by 171%, and decreases the return of Process 6, "NME repairs on-board LRU and returns it to ship," by 256%. Among the seven core processes, adding only 3D PDF increases Processes 2 and 5, "Replace operating LRU with warehouse spare" and "Replace on-board LRU with LRU cannibalized from another shop" most, by 532%, and decreases the return of Process 6, "NME repairs on-board LRU and returns it to ship" by 166%. Among the seven core processes, adding both technologies increases Processes 2 and 5, "Replace operating LRU with warehouse spare" and "Replace on-board LRU with LRU cannibalized from another shop" most, by 937%, and decreases the return of Process 6, "NME repairs on-board LRU and returns it to ship," by 73%.

Comparison of Royal Dutch Navy and U.S. Navy Scenarios

Previous research using the KVA approach developed estimates of returns on technology investment of a scenario in which the U.S. Navy adopts 3D LST and CPLM tools into the SHIPMAIN program. Komoroski (2005) investigated the early phases of SHIPMAIN (see Table 3). Adding the 3D LST and CPLM technologies improves the overall preparation for maintenance process ROI. Adding these technologies generally improves individual processes as well. The range of improvements across individual processes is large, varying

from 0% (Issue Tasking) to 3,031% (Generate Drawings). Cost reduction explains these differences. For example, the adoption of technology in Core Processes 4 (Conduct Shipcheck) and 7 (Generate Drawings) would significantly reduce the number of people required to survey ship conditions (4) or draft 3D drawings from the survey data (9), resulting in large ROI if the technology is adopted.

Seaman, Housel, and Mun (2007) used KVA to model the later phases of SHIPMAIN (see Table 3). Adding the technologies also improves overall maintenance implementation process ROI. Adding these technologies also improves each of the individual processes. The range of improvements across individual processes is large, varying from 6% to 466% (Final Install, Closeout SC), although not as wide as in the preparation for maintenance processes (see Seaman, Housel, & Mun, 2007, for details).

Table 3. Return on Investment: Baseline and Technology Adoption Scenarios

	Baseline Overall ROI	Technology-adopted Overall ROI
US Navy - SHIPMAIN (preparation for maintenance phases)	-27%	2019%
US Navy - SHIPMAIN (implementation phases)	35%	201%
Royal Dutch Navy (Damen experience extrapolation)	35%	274%

The three scenarios have some similarities. For all three, overall ROIs after technology adoption are positive and large. This supports the adoption of advanced technologies, such as 3D LST, 3D PDF models, and CPLM, to improve the efficiency of resource use. The scenarios also have potentially significant differences. The technology adoption scenario for the preparation for maintenance phases of the U.S. scenario has a much higher overall ROI than the ROIs for the maintenance implementation phases of the U.S. or the Dutch scenario (2,019% >> 201% or 274%). Several factors could explain these differences.

- The preparation for maintenance phases of the U.S. scenario have significantly lower ROI in the As-Is (without technology) condition (-27% > 35%). This suggests that inefficiencies in the preparation for maintenance processes provided more and larger opportunities for improvement.
- The individual preparation for maintenance processes that increased the most, such as Generate Drawings and Conduct Shipcheck, are very labor intensive and, therefore, costly, providing large opportunities for cost reduction through technology adoption.
- Several of the individual maintenance implementation processes are labor intensive but less impacted by technology (e.g., Install Shipcheck), thereby making those changes in ROI less dramatic.
- The preparation for maintenance phases of the U.S. scenario could be more optimistic in their projections than the other scenarios.
- The estimates of process changes may use different assumptions.

- Technologies adopted in the preparation for maintenance phases of the U.S. scenario may make much larger improvements in processes than those in the maintenance implementation phases of the U.S. or the Dutch scenario.
- The Dutch case does not use all of the capabilities of the CPLM, thereby making it more incremental than the U.S. scenarios, in which all the capabilities of the CPLM were projected to be used. Also, 3D PDF has more limited capabilities for integration with the CPLM logistics package when compared to the integration of 3D LST capabilities for broader usage in requirements analysis, planning for maintenance, and tracking of parts in the supply chain and across suppliers and contractors. This can partially explain the lower ROI for the Dutch technology-adopted scenario than for the U.S. preparation for maintenance scenario.
- The projections of the impacts on the maintenance implementation phases of the U.S. scenario and the Dutch scenario may be rather conservative based on research into the actual successful implementation of other modern technologies, such as RFID in inventory management. In a study of the actual use of passive RFID in two military warehouses in the Korean air force and army, the actual ROIs from use of the RFID technology were more than triple the projected impact of the use of the technology in a separate study of the U.S. Navy (Courtney, 1997). The Korean ROIs after actual implementation of the RFID technology ranged from 610% to 576%, compared to the projected returns anticipated from the implementation of the same technology in the U.S. Navy, which ranged up to 133%. The implication is that actual successful implementation of information technology in a military may exceed projections of the potential impacts of the technology. It follows that the current research on the impacts of CPLM and 3D LST or 3D PDF may be more conservative than the reality once these technologies are actually implemented on a wide-scale basis.

Integrated Risk Management Modeling and Results

Through the use of Monte Carlo simulation, the resulting stochastic KVA ROK model yielded a distribution of values rather than a point solution. Thus, simulation models analyze and quantify the various risks and uncertainties of each program. The result is a distribution of the ROKs and a representation of the project's volatility.

It is important to understand why it is necessary to apply uncertainty to the model. Because the KVA process provided a point value for each quantity, even though there was some uncertainty in the estimates provided by the subject-matter experts, application of the appropriate statistical distributions of input was used to restore the real world's uncertainty to the model. Having inputs from only three experts, as opposed to hundreds of estimates, and rather than using these three discrete inputs, we applied the lessons learned in cost estimating as reflected in the Air Force handbook (U.S. Air Force, 2007) as a good starting point for representing the uncertainty and reflecting it in the simulations.

Next, using the developed KVA model, risk simulation probabilistic distributional input parameters were inserted into the three main variables: percentage automation, time process is executed, and average time to complete. A risk simulation of 10,000–1,000,000 simulation trials was run to obtain the results.

At this point in the analysis, a proxy for revenues and volatility has been identified, as well as the numerators and denominators for the ship maintenance program. The next step

is to define or frame the alternatives and approaches to implementing 3D PDF and Logistics Team Centers, namely, strategic real options. The questions that can be answered include the following: What are the options involved? How should these new processes be best implemented? Which decision pathway is optimal? and How much is the program worth to the DoD?

Integrated Risk Management: Framing the Real Options

As part of the first round of analysis, Figure 3 illustrates some of the potential implementation paths for 3D PDF/Logistics TC. Clearly, some of the pathways and flexibility strategies can be refined and updated through the passage of time, actions, and events. With the evolution of the implementation, valuable information is obtained to help in further fine-tuning the implementation and decision paths.

For the preliminary analysis, the following options were identified, subject to modification:

- Option A: As-Is Base Case. The ROI for this strategic path is computed using the baseline KVA and this represents the current RDN ship maintenance process (i.e., no newly added technologies).
- Option B: Execute and implement 3D PDF and Logistics package immediately across all RDN ship maintenance processes. That is, take the risk and execute on a larger scale, where you would spend the initial investments and continuing maintenance expenses required and take on the risks of any potential failure, but reap the rewards of the new processes' savings quickly and immediately. The analysis is represented as the current RDN process altered to reflect what we estimate to be the impacts of adopting both a Logistics package and 3D PDF models.
- Option C: This represents the current RDN process altered to reflect what we estimate to be the impacts of adopting 3D PDF models and managing them in a Team Center or similar product. This technology was chosen largely because Damen is developing and pursuing the use of this technology.
- Option D: This implementation pathway represents the current RDN process altered to reflect what we estimate to be the impacts of managing using a Logistics module in a Team Center or similar product. This technology was chosen partially because it was a technology that Damen considered, but chose not to purchase.
- Option E: Proof of Concept (POC) approach. That is, to execute large-scale implementation of 3D PDF and Logistics Module in TC only after an initial POC shows promising results. If POC turns out to be a failure, we walk away and exit the program, and losses are minimized and limited to the initial POC expenses. Proceed to full implementation in POC programs first and then expand in sequential fashion to other programs, based on where best ROI estimates are shown.
- Option F: POC on 3D PDF only. Assuming the POC works and 3D PDF is executed within a few programs successfully, the learning and experience obtained becomes valuable and allows the shipyard to expand its use into many other programs or perhaps across the RDN.
- Option G: POC on Logistics Module in TC only. Assuming the POC works and Logistics Module is executed within a few programs successfully, the

learning and experience obtained becomes valuable and allows the shipyard to expand its use into many other programs or perhaps across the RDN.

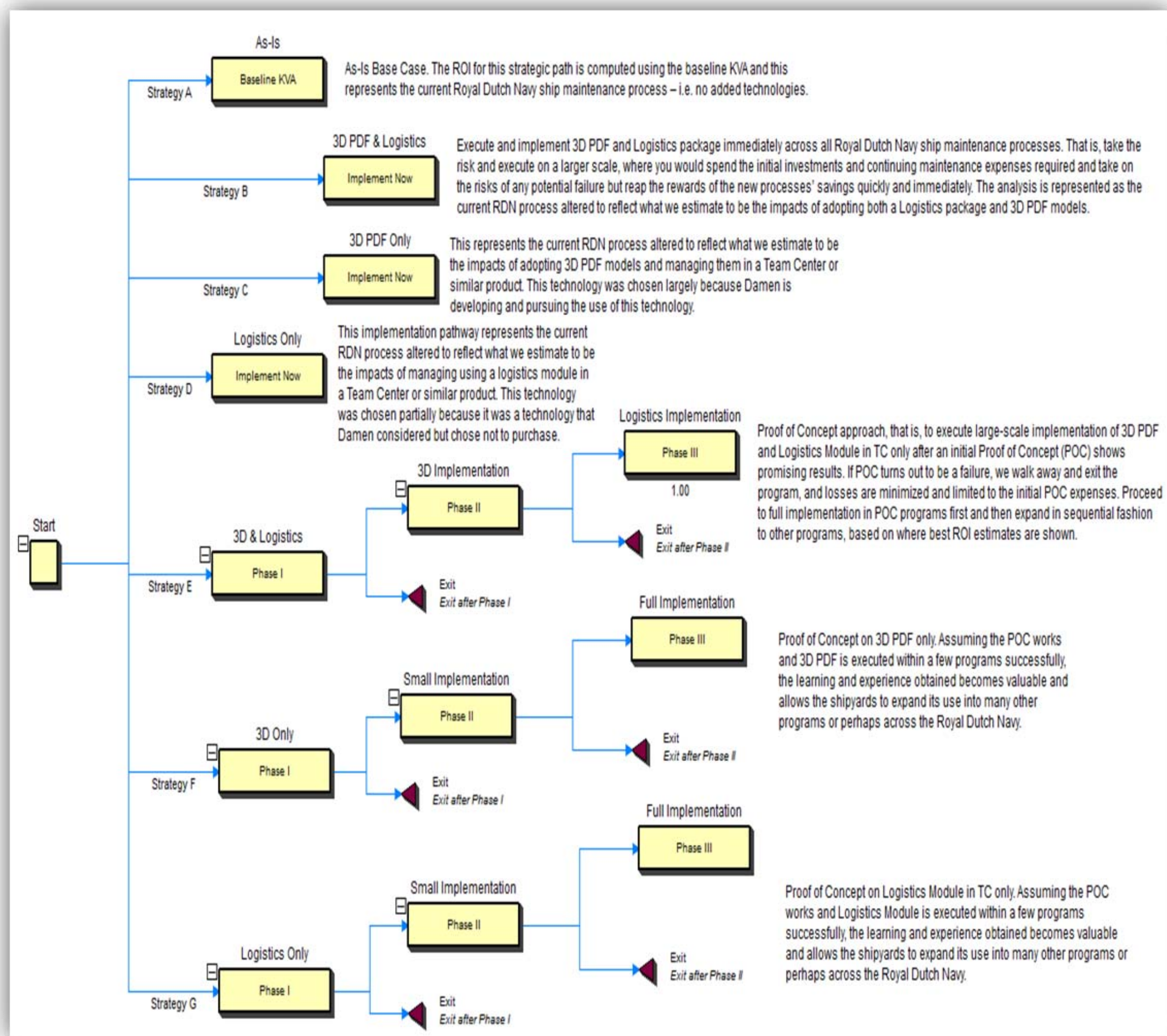

Figure 3. Sample Real Options Values

Integrated Risk Management: Strategic Flexibility Real Options Results

Figure 4 shows the results of the strategic real options flexibility values and compares them against the KVA ROI values. Options B ($154.1 million at 278% ROI) and E ($156.5 million at 282% ROI) of implementing both 3D PDF and Logistics Module TC return the highest ROI and total strategic value, and both provide a significant value-add above and beyond Option A's As-Is condition ($31.9 million at 35% ROI). As Options B and E are the most significant; stage-gating the implementation over several phases yields a slightly higher value (Option E exceeds Option B by about $2.4 million).

In addition, the Monte Carlo risk simulation results on the real options values were developed (but are not shown here for brevity; see Ford, Housel, & Mun, 2012). In comparing Options E and F, there is a 94% probability that Option E, which has a sequentially phased implementation of both 3D PDF and Logistics Module TC, provides a

better return than Option F. In comparing Options E and B, there is a 95% confidence that, even with all the uncertainties in the collected data and risks of implementation success, including uncertainties of whether the estimated returns will materialize and so forth, there is at least a $1.27 million net advantage in going with Option E. Therefore, it is better to sequentially phase and stage-gate the implementation over several years, allowing the ability to exit and abandon further stages if events unfold and uncertainties become resolved, so that further investment in the technology no longer makes sense. The risk-simulated real options value has an expected value (mean) of $195 million, with a corresponding average ROI of 363%.

ANALYSIS RESULTS

		KVA ROI	KVA ROK	Strategic Real Options	Real Options ROI	Volatility
Strategy A	As-Is	35.00%	135.00%	$31,903,557	35.00%	82.67%
Startegy B	3D PDF & LOGISTICS TC (IMPLEMENT NOW)	273.82%	373.82%	$154,163,806	278.53%	87.71%
Strategy C	3D PDF IN TC ONLY (IMPLEMENT NOW)	135.06%	235.06%	$96,330,730	137.25%	54.82%
Startegy D	LOGISTICS MODULE ONLY (IMPLEMENT NOW)	77.28%	177.28%	$81,009,562	91.66%	80.24%
Strategy E	3D PDF AND LOGISTICS TC (PHASED SEQUENTIAL)	273.82%	373.82%	$156,569,744	282.88%	87.71%
Startegy F	3D PDF IN TC ONLY (PHASED SEQUENTIAL)	135.06%	235.06%	$97,416,808	138.79%	54.82%
Strategy G	LOGISTICS MODULE ONLY (PHASED SEQUENTIAL)	77.28%	177.28%	$84,456,260	95.56%	80.24%

Net Differential: Strategy E over Strategy B	$2,405,938
Net Differential: Strategy E over Strategy F	$59,152,936

Figure 4. Sample Real Options Values

Summary Results of the Integrated Risk Management Analysis

IRM and strategic real options methodologies were applied to the KVA-SD results, and the results indicate that Option B had a value of $154.1 million (278% ROI) and Option E had a value of $156.5 million (282% ROI), where both options indicate that implementing 3D PDF and Logistics Module TC return the highest ROI and total strategic value and both provide a significant value-add above and beyond Option A's As-Is condition, with a value of $31.9 million (35% ROI). As Options B and E are most significant, we know that implementation of 3D PDF and Logistics Module TC returns the highest value and, when implemented over time in a stage-gate process over several phases, would yield a slightly higher value (Option E exceeds Option B by about $2.4 million). Therefore, we conclude that 3D PDF and Logistics Module TC implemented in a phased stage-gate environment would yield the best results. In comparing Options E and B, there is a 95% probability, even with all the uncertainties in the collected data and risks of implementation success as well as the uncertainties of whether the estimated returns will materialize, that there is a $1.27 million net advantage in going with Option E to sequentially phase and stage-gate the implementation over several years, allowing the ability to exit and abandon further stages if events unfold and uncertainties become resolved so that further investment in the technology no longer makes sense.

Conclusions

We collected new data on ship maintenance processes and the use and adoption of technologies in ship maintenance by the RDN and Damen Shipbuilding. The data were used to build and calibrate a system dynamics model of RDN ship maintenance. Model simulations of four technology adoption scenarios, reflecting the use of two available or developing technologies, generated estimates of maintenance operations behavior that

were imported into KVA models. The four technology adoption scenarios were then modeled in the KVA models. The KVA models estimated the ROIs for individual processes and ship maintenance as a whole for each scenario. Results were analyzed to reveal the relative improvement provided by individual, and combinations of, technologies.

The results of this study, in combination with prior studies, make it evident that the technologies under review will make large contributions to cost reductions in ship maintenance processes. These conclusions are supported by the comparative analysis of the Dutch experience with similar supporting technologies. There appears to be no empirical evidence that would serve as an impediment to adopting the technologies in the near term rather than the longer term. We recommend an immediate adoption of the 3D LST and CPLM technologies to support ship maintenance processes.

Implications for Acquisition Practice

The current research has significant implications for acquisition practice. First, the conclusions support multiple previous investigations that recommend the adoption of available information technologies to reduce the costs of U.S. Navy ship maintenance. Second, multiple significantly different technologies (e.g., 3D LST, 3D PDF, logistics support) can improve ship maintenance operations. Third, among those studied, the expensive information technologies were found to benefit high-cost processes the most, such as where labor can be replaced with technology. Doing so reduces costs and increases production rates by reducing cycle times. This implies that if technology adoption efforts are to be prioritized, those with labor-intensive processes that can be replaced with technology should be given higher priority. The real options analysis of implementation strategies demonstrated that some technologies (3D PDF in this case) can dominate the value space and that phased implementation adds value compared to one-step implementation. The results of the current work recommend a careful investigation of available technologies and how they improve operations, followed by a phased development and implementation of the adoption of the chosen technologies.

Implications for Research

The results of the three KVA-based studies varied significantly. A likely cause is the difficulty in accurately forecasting, in quantitative terms, the impacts of new technologies on specific processes. The use of data and information from organizations that are actively developing and adopting information technologies (Damen) and performing operations similar to those performed by the U.S. Navy (RDN) proved to be very valuable in improving the models (e.g., by adding the 3D PDF technology). Therefore, further refinement of the models should include actual application data, such as a study of actual technology adoptions by the U.S. Navy.

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Time as an Independent Variable: A Tool to Drive Cost Out of and Efficiency Into Major Acquisition Programs

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Abstract

With few exceptions, studies on improving the acquisition of weapon systems and services within the DoD observe that the process takes too long. A 2010 report of a study led by former Secretary of Defense William Perry and former Assistant to the President for National Security Affairs Stephen Hadley entitled *The QDR in Perspective: Meeting America's National Security Needs in the 21st Century: The Final Report of the Quadrennial Defense Review Independent Panel* supported this point of view, asserting that no defense program should exceed seven years. In a September 14, 2010, memorandum, the Under Secretary of Defense for Acquisition, Technology, and Logistics called for the DoD acquisition community to "set shorter program timelines and manage to them." But what is the right timeline for a given defense program? The author offers a methodology for making that determination through a process using time as an independent variable (TAIV™)[1] in a way similar to using cost as an independent variable (CAIV). Using TAIV™ establishes a credible way of reconciling cost, capability, and the time required to field a needed capability.

Introduction

Although the work done in assessing the value of using time as an independent variable (TAIV™) is not a panacea, there are clearly acquisition programs where cost and performance should vary with program management conditions that recommend accepting more performance at an increase in cost. What the National Defense Business Institute (NDBI) has found is that assessing a capability relative to the time necessary to achieve that capability is a useful effort. TAIV™ can be a valuable tool to that end.

From the end of the Korean War to the present, the length of time required to field a Major Defense Acquisition Program (MDAP) has persistently grown as a common practice. In their assessment *Streamlining DoD Acquisition: Balancing Schedule With Complexity*, James Rothenflue and Marsh Kwolek (2010) put it more bluntly:

> Since at least the late 1960s, the Department of Defense has been trapped in an escalating cycle of cost overruns and schedule delays on large acquisition programs. In particular, state-of-the-art aircraft programs have ballooned from one to five year sprints during and immediately after World War II to the 25-year marathons of the present day.

With the ever-increasing length of time taken to field weapon systems, total program costs have risen as well.

[1]TAIV™ is an acronym trademarked by Monitor Government Venture Service, LLC, during the course of their research and analysis of the use of time as an independent variable, sponsored by the Office of the Deputy Secretary of Defense.

Analysis over time shows that acquisition programs generally grow about 50% in cost (Younossi et al., 2006), and of course larger defense programs have higher stakes owing to the sums of money involved compared with programs managed by other federal agencies. Programs with longer timeframes for engineering, manufacturing, and development also experience greater cost growth (Younossi et al., 2006). Furthermore, almost all acquisition strategies lack the analysis as to what time does, as an independent variable, to the trade space defined by the minimum and optimum performance and cost.

Two recent commentaries on the crucial nature of time as a key element in acquiring weapons and military equipment come from different quarters, but they agree on the way forward. In a 2010 study, two former senior government officials argued that study, which was led by former Secretary of Defense William Perry and former Assistant to the President for National Security Affairs Stephen Hadley entitled *The QDR in Perspective: Meeting America's National Security Needs In the 21st Century: The Final Report of the Quadrennial Defense Review Independent Panel.* Hadley and Perry (2010) were quite clear in their recommendation, explaining,

> Permitting delivery times longer than a reasonably achievable standard is counterproductive to both the demand for responsiveness to current needs and tomorrow's challenges. For major programs for future forces, useful increments of military capability should be defined as what can be delivered within 5 to 7 years with no more than moderate risk.

Under Secretary of Defense for Acquisition, Technology, and Logistics, Dr. Ashton Carter, also addressed the issue of time in a 2010 memorandum to acquisition professionals titled *Better Buying Power: Guidance for Obtaining Greater Efficiency and Productivity in Defense Spending.* As one of his 23 principal actions "to improve efficiency" in the DoD acquisition efforts, Dr. Carter mandated, "Set shorter program timelines and manage to them."

The significance of time to more efficient acquisition of military weapons and equipment is not new. The Special Assistant to the Deputy Secretary of Defense in 2004 asked the Monitor Group (Monitor Company Group LP, 2003) to look at the value of establishing time as a boundary condition or driver in determining the desired timeframe between Milestone B and initial operating capability. Time should be considered an independent variable (TAIV™), especially when it is critical to field a capability on a specific point in the future to have a positive impact on a threat or in the course of ongoing combat. Because there is little direct research on TAIV™ specifically, the Monitor Group work done for the Office of the Deputy Secretary of Defense and subsequent analyses completed for the Under Secretary of Defense for Acquisition, Technology, and Logistics (2006) establishes most of the foundational thinking on using time to establish time as a structured way to determine the limits or boundaries of acquisition programs. However, it is equally important that there be a reliable, valid process for the DoD to "evaluate, acquire and deploy" the most current and effective technology for "long-term performance and mission accomplishment" (Sherman & Rhoades, 2010).

Unfortunately, the idea did not gain traction in 2004, for two related reasons. Among the acquisition community, there is a pervasive belief that a capability is selected to address a requirement that then takes as long as it takes. Such an attitude carries with it no discipline or structure and allows for program success to be dependent on yet-to-be-realized inventions and even miracles. That lack of discipline creates a work environment governed by manufactured job security rather than efficiency. By allowing programs to be temporally

indeterminate, government employees and contractors have no incentive to bring projects to closure, allowing programs to drag out for longer periods of time.

Times have changed, and the pressure is intense to reduce the time it takes to put weapon systems and equipment in the field and simultaneously reduce the costs that attend prolonged and stretched programs. The time is opportune for applying the TAIV™ tool for new acquisition programs, as well as to block upgrades to existing programs.

Applying TAIV™

How should TAIV™ work in a practical sense? When the Monitor Group in 2004 attempted to use time to drive discipline and structure into the acquisition system, the idea was to use TAIV™ to enable the DoD's transformation initiatives as a supporting acquisition framework. There was sense of urgency in getting needed weapon systems and equipment to the warfighters in both Iraq and Afghanistan.

If TAIV™ is to be used and applied to the full program life-cycle, then the TAIV™ analysis must start early in the acquisition program concept development and acquisition process. TAIV™ must be an essential part of the acquisition strategy, solicitation process, and contract development activities.

The DoD generally pursues one of three approaches when acquiring a weapon system or piece of equipment: single step to full capability, incremental development, or spiral development. Incremental and spiral development are grouped under the category of evolutionary acquisition strategy (DoD, 2011). The acquisition approach must consider what the desired end state of the program is to be and determine the appropriateness TAIV™. Single-step to full capability can apply TAIV™ successfully when the end-state requirements are known and can be used to set program length, program milestones, and incentivize compliance. Additionally, the technology must be mature. Commodity parts and immediately available capability would fit the single-step to full-capability category.

Applying TAIV™ to an incremental development approach fits when the end-state requirements are understood and when multiple development cycles are anticipated. Again, mature technologies are required, as well as threats that can be addressed with minimum rather than assured operating capability. TAIV™ would be used to set the increment duration and would be useful as an incentive to drive compliance.

The last acquisition approach, spiral development, is most appropriate when multiple development cycles are anticipated and the acquisition program will produce interim outputs. End-state requirements may not be certain. Programs in this category may have some level of exploratory development, but with mature technology. To address threats effectively, sufficient capability is required sooner, rather than assured or objective performance capability later.

Generally, when time is the subject of research, it is used in terms of reducing cycle time for acquiring systems and equipment, or in other words, looking at the time from program start to delivery from the top down. The intent is to simply compress or streamline the acquisition process and drive time out with "levers for reducing cycle time" (Sherman & Rhoades, 2010). The traditional approach emphasizes ways to reduce time spent on activities or events that are in progress. TAIV™ takes an alternative approach by establishing, from the outset, what performance or capability is possible based on the time-defined construct, or when the weapon system or equipment must be in the field. Once the capability available to the time-defined limit is determined, then the program will be driven to that boundary.

The green line in Figure 1 represents the sequence of technology maturation over time. The TAIV™ process looks at the maturity and relevance of a necessary technology that provides a warfighting capability starting at the beginning of the technology maturation line (point 1). The distance between points 1 and 2 represents the time necessary to develop, adapt, or exploit a maturing technology and turn it into a capability. Point 2 is the best time-to-field versus capability increase. It is at this point that the maximum amount of capability for the technology available is realized. The timeframe represented by point 3 allows for fielding and follow-on production of a capability. Taking additional time to develop a particular technology will not provide marginally greater capability until point 4, when there is another technology breakthrough. As demonstrated, TAIV™ puts the emphasis on fielding capability when the technology supporting the capability has its greatest value. That value is defined by the lack of an equal alternative technology that meets the time-defined capability.

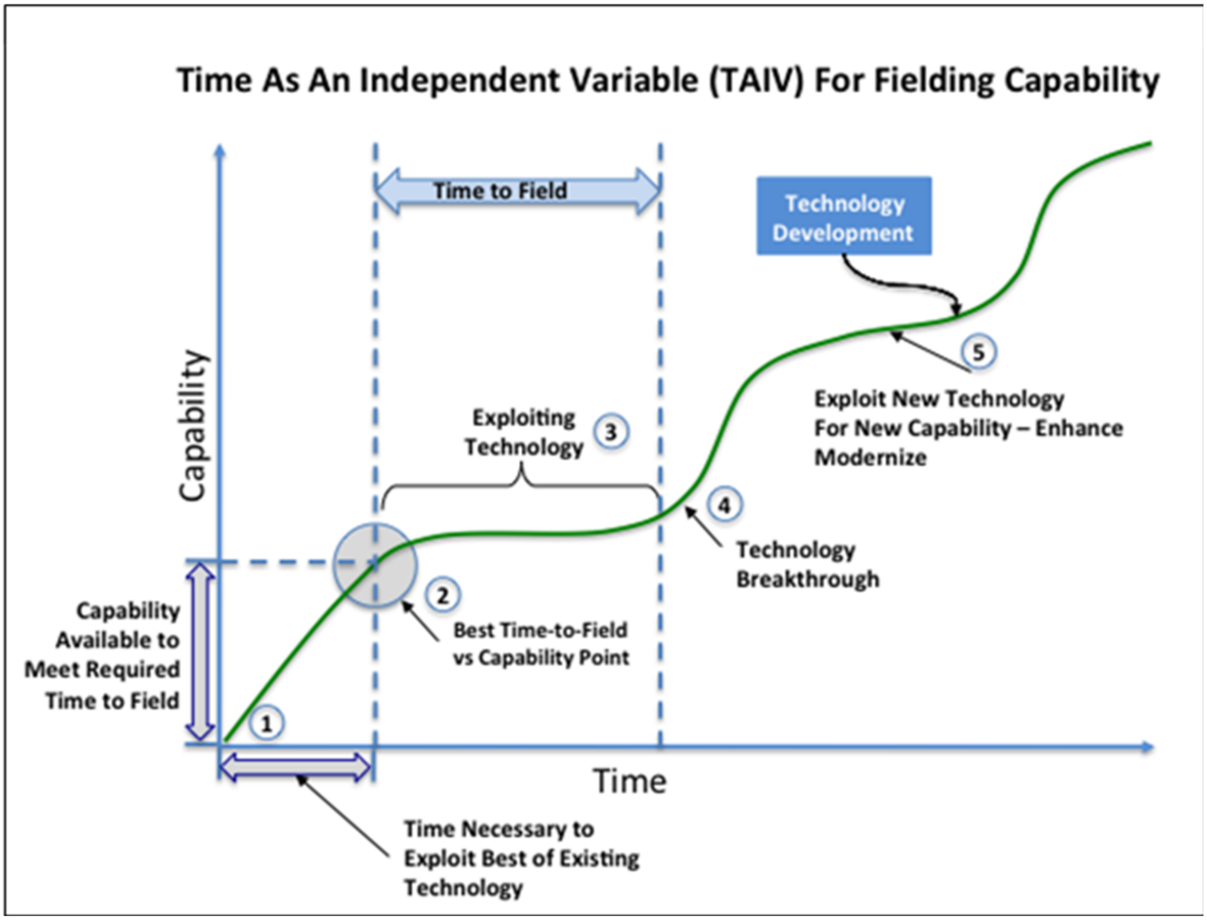

Figure 1. Time as an Independent Variable (TAIV™) for Fielding Capability

Note. Identifying the "Critical Time vs. Capability Point" where extending the time does not achieve a marginally greater degree of capability is the analytic value of TAIV™.

Coincidentally, the technologies that underpin the capabilities that might be needed in the future continue to mature. Over time, significant breakthroughs occur, increasing the potential for ever-greater capability, but only after a capability has been fielded. When additional time spent on development of technology no longer increases the level of capability, that is the critical time to field a capability. The existing technology should be exploited from that point until there is another technology breakthrough or dramatic technology increase.

Should the need for a capability be more urgent because of a more near-term threat, the level of technology may have to be less capable. In such a case, an appropriate strategy would be single-step to full capability. Commercial off-the-shelf (COTS) technology provides a solution with little or no need for integration or development time and would aid in putting a capability in the field in the least amount of time. The concept of using time to drive the level of technology that defines a capability can be used to assess the appropriate capability and performance trades.

The challenge for the acquisition community is twofold. First, the point in time must be established at which a weapon system should be fielded. Second, the available COTS capability must be determined in terms of what can be most easily developed. As Figure 1 shows, getting greater capability to the field earlier relies on exploiting what is available that requires little or no development. The ideal condition achieves operational capability at the point where additional time does not gain appreciably greater capability—the critical time versus capability point, or the knee in the TAIV™ curve.

The crux of the TAIV™ tool's value comes from its ability to reveal the amount of time necessary to meet a required fielding date with the most capability.

As depicted in Figure 1, the TAIV™ process satisfies all three of the acquisition approaches described previously. Single-step to full capability can be achieved when the end-state requirements are certain; incremental development using TAIV™ when both end-state requirements and multiple development cycles are criteria; and a spiral development approach would benefit from TAIV™ when multiple development cycles and interim outputs are anticipated.

Figure 2 represents how threshold and objective performance parameters can frame the trade space for achieving the target delivery of a capability. Again, time establishes the boundaries.

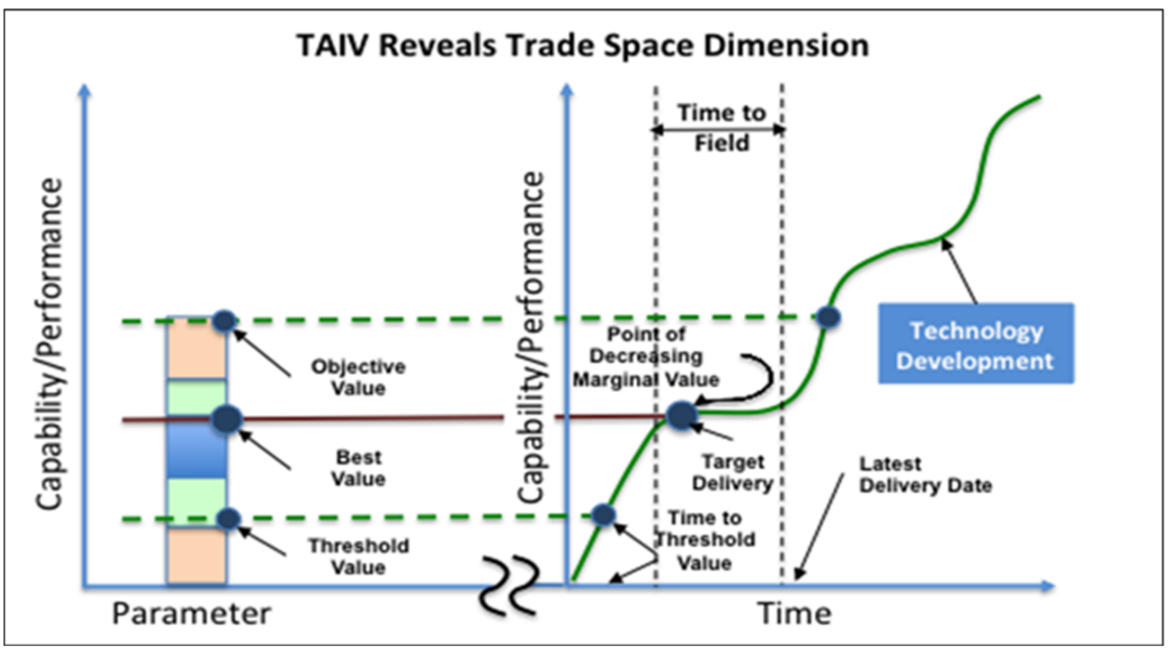

Figure 2. TAIV™ Reveals Trade Space Dimension
(adapted from 2004 Monitor Group briefing)
Note. TAIV™ provides a means of identifying the best value performance solution to field an effective capability at a target delivery time.

Establishing capability and the desired performance with objective performance value and minimum acceptable or threshold performance value frame the capability performance necessary to meet a requirement and address a threat. The trade space becomes the time between the earliest that the threshold performance can be met and the latest delivery date before the risk of significant damage. Again, the target delivery date is defined as that point in time where the most capability or performance can be achieved, after which continued pursuit of "better" performance has little or no increase in capability before the latest delivery.

The target delivery date is also the point in the future when the best capability over time can be achieved at the best value.

It is a reasonable assumption that acquisition programs, guided by earliest and latest acceptable time-to-field, possess a credible understanding of the threat to be addressed by the capability. Here again, having TAIV™ as a tool lends credibility to the argument advocating for a particular capability being fielded at a particular point in future.

TAIV™ Integrates Threat Assessment, Time-to-Field With Available Technology

TAIV™ is useful in helping determine the greatest capability over the least amount of time, but some forcing function must be present to actually define the "least amount of time."

At minimum there must be some understanding of the driving requirement that addresses an understood national security threat. Then "the least amount of time" becomes the time to field the weapon systems or piece of equipment.

Figure 3 illustrates the relationship among time, capability, and technology progress when compared to the window of understanding represented by the threat a potential enemy. Over time, there is less fidelity in the understanding of threat in terms of the lower and upper limits of the capability necessary to meet a requirement to address the threat. The clearest and most credible understanding of the threat has the most fidelity in the near term. Understanding of the threat declines as the assessment of that threat is pushed further into the future.

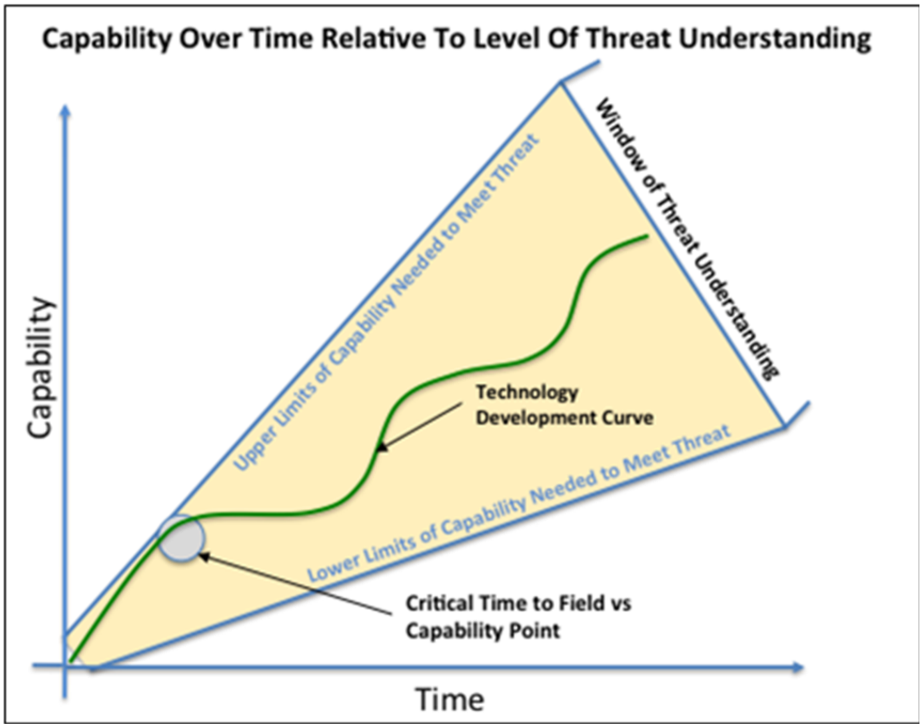

Figure 3. Capability Over Time Relative to Level of Threat Understanding
(adapted from 2004 Monitor Group briefing)
Note. As planners attempt to assess the threat to national security, there is less fidelity and accuracy possible the further into the future the assessment is made.

Additionally, as Figure 3 suggests, using TAIV™, it is more likely that the capability possible in the near term (and more in line with the critical time-to-field) will be more appropriate to meeting the requirement to address a threat.

When TAIV™ is applied to the development of an acquisition program, the importance of time in developing and defining the technology, as well as its design and production, is more dominant in the analysis of cost, schedule, and achieving the desired performance. *Time-defined* in this instance, however, is not synonymous with schedule.

Though a 2009 GAO report points out that a DAPA report recommends that schedule be a key performance parameter (KPP), this paper looks at the time between the beginning of a program and the point at which a weapon system is operational as a time-defined period. By that definition, the specific length of *time*, and not schedule, is a KPP.

Schedule is the sequential distribution of program events when, on completion, they have a timeframe associated with them. We measure schedule with milestones accomplished. TAIV™, on the other hand, is the analytic construct that identifies which performance capabilities are important and must be achieved, and conversely, which are of marginal value when considering the time from development to incorporation into the weapon system to fielding to consideration for future block upgrades. The time-defined period is established with the results of the TAIV™ analysis.

Various recommendations exist for the timeframe for development and fielding: Hadley and Perry (2010) suggested five years for fighter type aircraft and eight years for ships, and five to seven years for all programs; in a DAPA report, Kadish (2006) recommended "nominally no more than six years for major platforms from Milestone A" to

fielding. Without a way to appropriately evaluate time, acquisition programs will continue to take "as long as they take."

Although a 2009 GAO report points out that the DAPA report (Kadish, 2006) recommended that *schedule* be a KPP, this paper looks at the time between the beginning of a program and the point at which a weapon system is operational as a time-defined period and that specific length of *time* be a key performance parameter, not schedule.

The reason for distinguishing between time and schedule is to give precedence to the time-to-field as a weapon system or piece of equipment that should take precedence over a particular sequence of program events or activities. The integrated master schedule (IMS) can be modified during the course of program duration without doing violence to an established critical time to field the weapon system or piece of equipment. Establishing a program schedule as a KPP would suggest that to modify the schedule while not changing cost and performance or the time-to-field would constitute a failure to meet a KPP, but that would not necessarily hold true. Making schedule a KPP simply adds a level of complexity to the concept of TAIV™ without corresponding value.

Urgency for fielding a particular desired capability, then, has a context that can be used to describe what needs to be fielded or deployed and when. Again, Kadish (2006) fortified this line of thinking, saying, "Once the time-to-need and the current technology risk level are determined the program should be time-constrained."

The TAIV™ curve conjures the "cost as an independent variable" curve owing to the analogous relationship that results from the adage "time is money." But there is a clear distinction: cost may vary with time, but not directly. Many variables that include quantity and quality determine cost, but time is immutable. Just as, at a certain point, increasing dollars spent on a program will not produce a corresponding increase in capability, increasing time spent will also not produce a corresponding and direct increase in capability. Technology and innovation must come into play. Rene Cordero made this point in a 1991 discussion of "managing speed" in getting products to market to avoid obsolescence: "Finally, the natural limits of the technology are reached and only small improvements of the product are possible." That point in Figure 1 is the best time-to-field versus capability point.

Similar to a time-to-market requirement, the unified command's assessment of when a capability must be fielded becomes a crucial factor in evaluating the amount of time to devote to fielding a new weapons program (see Figure 4). Timing plays a crucial role when introducing a new product and maximizing market share; similarly, weapons must be in the hands of warfighters at the optimum moment on the battlefield.

Figure 4. Market Pressures Analogous to Meeting National Security Threats

Note. As the competitive environment for commercial goods and services drives the necessary time-to-market to have a market edge, the understanding and certainty of the emergence of a threat to national security drives the required time-to-field weapon systems and military equipment.

Just as there is an optimum time for a new product to be introduced in order to capture the most market share, there must be some idea of when a weapon must in the hands of the warfighters to achieve the desired effect on the battlefield. The time-to-market drives new product development in the same way that battlefield requirements to address a threat drive weapons acquisition programs. Consequently, the time-to-market demand will be a surrogate for the time-to-field requirement for weapon systems.

For the purpose of this paper, the competitive market pressures driving critical time-to-market decisions are analogues to identifying military threats that drive the critical time-to-field. Competitive pressures in business have caused product life cycles to compress, and subsequently, companies have taken measures to shorten their development cycles, thereby getting products to market faster (Griffin, 1993). Getting to the fight with the right equipment in time to make a difference against the threat is a DoD priority.

Value of TAIV™ Throughout Acquisition Program

When TAIV™ is applied, there are several benefits that result. The obvious advantage is that an effective capability is fielded sooner and at less cost to the government. The capability may be minimally sufficient, but it is sufficient. Additionally, TAIV™ has the potential to modify behaviors that have the potential to be costly, disrupt schedule, and threaten system performance. Figure 5 lists some of the behaviors that TAIV™ can influence positively.

When the duration of an acquisition program is constrained by specific timeframes with the threat of cancellation for exceeding those limits, events like milestones and reviews will be viewed with greater significance. Developmental engineering, systems engineering, and sustaining engineering will approach engineering tasks constrained by time as engineering challenges to be met as they would any other engineering tasks. To establish the importance of TAIV™ as a legitimate and critical program management tool, DoD acquisition management leadership should conclude that mandating a policy that threatens program cancellation for missing time-defined milestones is necessary for establishing and maintaining program internal control.

TAIV™ Can Improve Results Tied To Acquisition Management Behaviors

- Unambiguous timeframe defines Contractor and DoD management performance
- Time constant that bounds the engineering tasks
- TAIV™ policy to mandate time-defined milestones or risk program cancellation
- Reduces level of optimism within DoD acquisition community
- Reduces prime contractor's inclination to over-promise
- Helps to limit the conspiracy of hope
- Test community more likely test to immediate requirements
- Engineers less likely to over-design
- Time constrains limit the cost impacts of external program influence

Figure 5. TAIV™ Can Improve Results Tied to Acquisition Management Behaviors

Note. When acquisition program duration has no time constraints, unintended and negative program management behaviors result. TAIV™ helps to establish constraints of undesired behaviors.

Programs so often fall prey to a misplaced sense of optimism by program managers prone to believe that success is inevitable, despite evidence to the contrary. The constant

imposition of time constraints reduces that inclination toward optimism. An equally insidious and destructive behavior that grows with the government's optimism is the contractor's desire to please the customer, which leads to over-promising. The result, according to Kadish (2006), was that "the culture of the Department [of Defense] is to strive initially for the 100 percent solution in the first article delivered to the field." Kadish (2006) went on to say, "Further, the 'Conspiracy of Hope' causes the Department to consistently underestimate what it would cost to get the 100 percent solution. Therefore, products take tens of years to deliver and cost far more than originally estimated."

The test and evaluation community must be disciplined by the same time constraints as the rest of the program management. That means the Test and Evaluation Master Plan is constrained and managed to operate within the program time limits. With a mature technology necessary for TAIV™ to be appropriate, the challenges of the test community will be correspondingly reduced to live within the TAIV™-established timeframe.

Time constraints will by design lead to shorter time cycles, and with those shorter time cycles the tendency to "future-proof" the weapon system or equipment. Consequently, over-designing will be discouraged, and the temptation to try and anticipate a future design requirement will be less likely.

Lastly, one of the most disruptive and intrusive influences comes from external sources. Whether it is Congress, agencies in the executive branch, or the grass roots activities of other suppliers, with limited time for program execution comes limited time for these external actors to influence the program execution, causing delays, increased cost, and potential reduced program performance.

There is a value to TAIV™ that is not immediately apparent; but when evaluating the challenges of developing an acquisition strategy that drives desired contractor behaviors, it should be considered. As part of an in-depth look at "Evaluating MDAP [Major Defense Acquisition Program] Contractor Incentives," a research study conducted by the NDBI for the Director, Performance Assessment, and Root Cause Analysis Directorate, the NDBI found that for contractor incentives to be effective, they had to be "focused, clear and specific, measurable and achievable as well as motivating." An analysis of TAIV™ in this context is revealing.

Figure 6 represents a comparison between total acquisition program cost on the y axis and program duration (time) on the x axis. As time or program duration increases, so does the total cost of the program. From Figure 2, the goal or objective time is plotted against the target delivery time and the threshold time to field. In this case, the threshold becomes the longest program duration after which the rise in cost (maximum cost) makes the program of "questionable value to continue." Ideally, the target cost (best value) and target delivery or fielding date are synchronized, once TAIV™ is exercised.

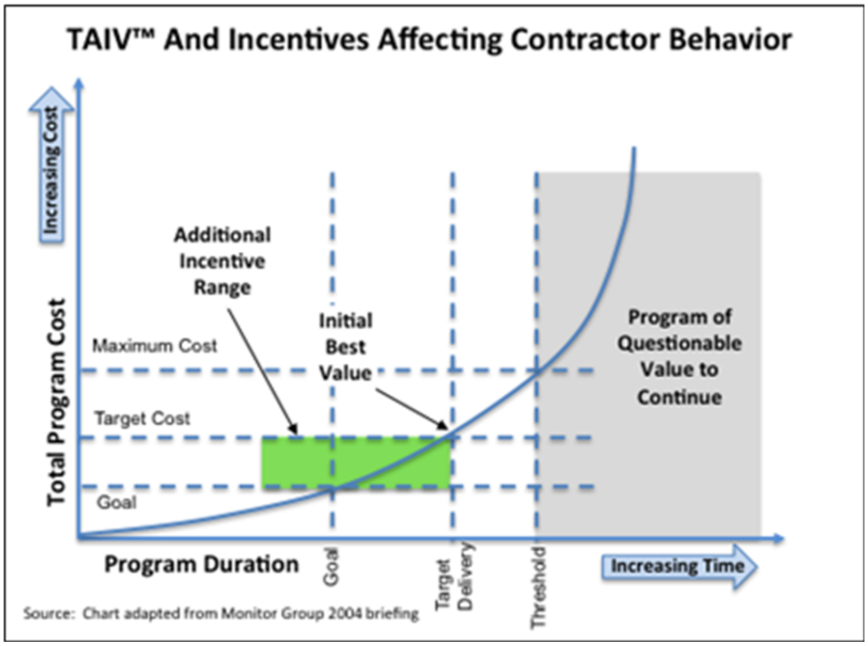

Figure 6. TAIV™ and Incentives Affecting Contractor Behavior
(adapted from 2004 Monitor Group briefing)
Note. TAIV™ can be used in trade studies that reveal where to offer incentives to prompt contractor behavior that increases value to the government. Larger incentives could be considered to move program delivery into the "Additional Delivery" range for early delivery.

The contractor would be incentivized to strive to perform in the green shaded area. This is the area where the contractor can work to lower program cost by delivering a quality product earlier. The lowering of the program cost is achieved by reducing the time to deliver the weapon system to the field.

Larger incentives can be achieved by reducing the time to deliver into the "additional incentive range." Using TAIV™ creates the trade space to fulfill the criteria for an incentive to be effective. The incentive is focused on the performance parameter of fielding the weapon system sooner than the target delivery time and at lower cost as a result.

The incentive is clear and specific since establishing a time-defined target delivery point in the duration of the program execution. The contractor meets the target delivery point, achieves an earlier delivery, or misses the delivery target. Contract terms and conditions can be crafted to provide a penalty for missing the target delivery as a disincentive.

TAIV™ allows for the criteria for incentives to be measurable and achievable because, again, the program deliverables either are early, meet the target date, or are late. The analysis that accompanies the TAIV™ analysis will take into consideration the level of technology maturity in determining the target delivery.

The incentive must be motivating. If the previous three criteria are met, creating an incentive with a magnitude of value to the contractor becomes a matter of negotiation. The terms and conditions of the contract establish the value of the incentive, but with TAIV™ there is much less ambiguity around establishing the incentive value.

Conclusion

With the emphasis on greater efficiency in acquiring weapon systems and equipment, better buying power and the more timely fielding of weapons can benefit from a

more disciplined and structured approach to the process. Eliminating unproductive processes and bureaucracy by reducing “cycle times while ensuring sound investment decisions” (Kendall, 2012) would benefit from implanting TAIV™ in some form or fashion.

Budget pressures are more intense now than they have been in nearly five decades. Inefficient use of scarce resources simply cannot be normal order. TAIV™ provides a disciplined and structured process for achieving the most capability and best-value cost in the least amount of time to be effective. TAIV™ eschews the one-size-fits-all downside of other approaches to reconcile threat, time-to-field, and cost. Rather, TAIV™ is self-tailoring to prompt an appreciation of how using time to establish boundaries can drive efficient acquisition program execution.

The historical record of acquisition reform reports and recommendations is almost unanimous in its view that, as Kadish (2006) put it, “The acquisition process is slow, overly complex and incompatible with meeting the needs of multiple, competing, departmental demands, in a diverse marketplace.” TAIV™ has the potential to expedite the process to field the best value defense product with a level of complexity consistent with the requirement to meet the understood threat. The resulting fielded capability will meet the demands of the only customer of importance—the warfighter.

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The Impact of Globalization on the U.S. Defense Industry[1]

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Introduction

The nation's military strategy, in large part, continues to depend on superior technology, highly qualified operational forces, and the ability to sustain those forces in order to achieve its objectives. However, the global industrial base (as well as the U.S. industrial base) no longer exists as it did during the Cold War, and the DoD must seek to gain the benefits of globalization.

In the past, the U.S. industrial base would ramp up to meet the needs of the U.S. military and then fade into the background when the conflict was ended. Throughout the Cold War however, the defense industry became a permanent segment of the industrial base, providing dedicated development and production of the systems, equipment, and supplies. The approach was to not to mobilize for conflict but to have enough permanent

[1] This is a summary of the full report, which will be available in July 2013.

capacity within the defense industry to address it (Gansler, 1980). The industrial base, however, no longer exists as it did during the Cold War.

The Cold War's end ushered in the following developments that came to dominate the restructuring of the defense industry. First, deep cuts in defense spending forced a major consolidation, down to a small number of defense-dedicated firms. Shrinking defense budgets in the 1990s resulted in a string of mergers of defense industry suppliers. In 1993, there were 21 companies doing major defense and aerospace work; today, there are six U.S.-based companies: Boeing, Lockheed Martin, BAE Systems, Raytheon, General Dynamics, and Northrop Grumman. Small and large suppliers alike—especially if they can survive on commercial business alone—consider government accounting and reporting requirements burdensome, and many have stopped bidding on government contracts, thereby reducing the stream of suppliers. In many critical defense areas, the number of suppliers remaining—at either the prime contractor or lower-tier levels—is down to only one or two. And with the likely future stabilization or decline of defense budgets, this consolidation trend is potentially going to increase. Second, the commercial sector began to invest heavily in high-tech research and development and technological advancement. Third, globally dispersed technology development and production has left the U.S. dependent upon off-shore sources for critical defense-related technologies (especially in critical, lower tier component areas). Finally, there was a shift in emphasis within the DoD from weapons and systems to complex communications and information technology. As a result of these, the former U.S. defense industry,[2] almost without exception, is transforming itself (through consolidations, mergers, acquisitions, joint ventures, and integration that crosses national boundaries) into a global, more commercially oriented industry (Defense Science Board, 1999).

As a result of these four changes, the formally segregated defense industries of Western countries are in the process of transforming themselves (through consolidations, mergers, acquisitions, joint ventures, and integrations that cross national boundaries) into a global, more commercially oriented industry. Take, for example, the DoD's new MRAP vehicles. They use a V-shaped hull that was originally developed and refined in South Africa, armor designed and developed in Israel, robust axles from Europe, and electronics from Asia (Gansler, 2009). The rest of the world's defense industry is also becoming more flat. Just recently, the United Arab Emirates introduced a new corvette class ship, built by Abu Dhabi Shipbuilding.

> But little of what the company featured came from the UAE. The design of the planned fleet of six Baynunah-class ships originated at Constructions Mecaniques de Normandie of Cherbourg, France. The fire control, and command and control for the weapon systems came from Italy. The Exocet and SeaSparrow missiles were built in France and the United States, respectively. South Africa's SAAB Avitronics supplied the laser warning system. German companies provided the decoy system, the sonar, the underwater communications and the engines. (Magnuson, 2011)

This tendency toward globalization—the tendency of markets for goods, services, and capital to transcend national boundaries and become interconnected—is not new; Ford and General Motors were assembling cars in 24 countries in 1928 (Sturgeon & Florida, 2000). The term *globalization* was first used and identified as an unstoppable process

[2] The Europe Community has similar concerns, and is working on developing a Community security strategy and industrial policy (Hartley, 2006; Markusen & Costigan, 1999) .

almost 25 years ago (Levitt, 1983); it has significantly accelerated with advances in communications and computer technology.

Current U.S defense trade and industrial policy does not clearly address globalization or its implications. Instead, the current U.S. policy is the consolidation of numerous incremental changes, often contradictory in their aims. For example, the National Security Strategy seeks to open markets and increase military cooperation, while export controls and “buy American” laws inhibit the international trade in defense products (McLean, 2005). Furthermore, other factors such as International Traffic in Arms Regulations (ITAR) and export control laws disincentivize commercial firms from entering the defense market. When commercial technology has military applications, the State Department requires compliance with export control laws prior to exportation. These restrictions often make commercial firms think twice before entering the defense market, because their goods may be restricted in the commercial market. For example, in the construction of Boeing’s new 787 Dreamliner, significant concern was raised over similar components that were also used in the Air Force’s B-2 Bomber (Gates, 2006). Finally, restrictions are not made for goods alone but can have an impact on the availability of labor as well. For example, restrictions on security clearances or visas for foreign nationals often make it difficult for U.S. firms to gain access to the best and brightest minds from around the world to work on highly technical fundamental research programs.

However, since the globalization of the defense industry is a relatively recent phenomenon, its impacts have not yet been fully realized, or understood. Recent comprehensive studies of the U.S. defense industry (since the end of the Cold War but before the September 11, 2001, terrorist attacks) have focused on the then perceived overcapacity, downsizing, and conversion of the defense industry (Gholz & Sopolsky, 1999–2000). Although acknowledged as a growing trend, globalization is recognized for its benefits along with its risks, as well as the lack of a consistent and cohesive national policy (Gansler, 2011; Markusen & Costigan, 1999). RAND examined the impact of globalization on the defense aerospace industry and identified many benefits, and some risks but called for more research on the issue (Lorell et al., 2002). Finally, a study by the National Research Council (Dr. Jacques Gansler participated in the study) examined the availability of the U.S. critical technology in a globalized environment and recommended the development of monitoring capability of both U.S. industrial health and component unavailability (National Research Council, 2004). Lacking from these studies is a comprehensive examination of globalization’s impact on the defense industrial base and national security.

The commercial sector (which pays little attention to national boundaries) is now driving the development of advanced information technology, required for most military systems, and is already very global. Manufacturing industries were found to be more globalized in major industrial countries, although lagging in the U.S. (Makhija, Kim, & Williamson, 1997). Original equipment manufacturers are increasingly contracting out their manufacturing and focusing exclusively on the product design and marketing (Sturgeon & Florida, 2000). Moreover, the source of competitive pressure is shifting from the globalization of markets to the globalization of production, and with it the key competitive advantage has begun to shift from excellence at the point of production to excellence in governing the spatially dispersed networks of plants, affiliates, and suppliers (Sturgeon & Florida, 2000).

When globalization is viewed through the prism of international trade, White House staff have argued that the impact of increased job exportation, offshoring (Mankiw referred to it as *outsourcing*) is just another form of trade and “would ultimately benefit the United

States” (Andrews, 2004). Other research has supported this view and concludes that offshoring leads to gains from trade and increases to national income, with minimal negative job impact (Bhagwati, Panagariya, & Srinivasan, 2004). Gomory and Baumol (2000) argued that the modern free-trade world is very different from original free-trade models, and that with modern industries, dominance can occur as a result of “the vagaries of historical accident.” Once these patterns are established, they tend to be preserved and are less influenced by free-market forces; therefore, they suggest that government policy should favor the high-value retainable industries (Gomory & Baumol, 2000).

Although the globalization of the defense industry is not a relatively recent phenomenon, its impacts have not yet been fully realized or understood.

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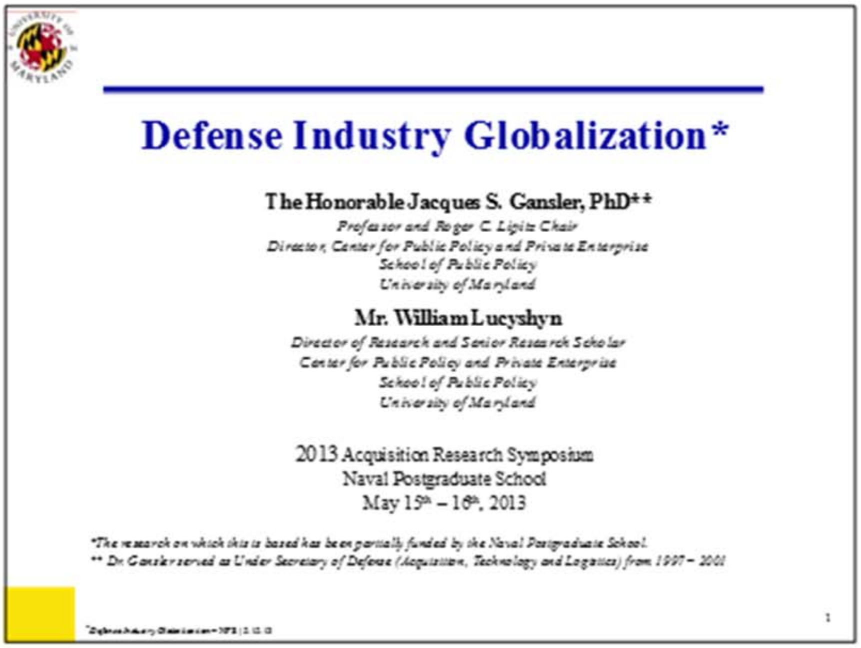
Appendix



"God did not bestow all products upon all parts of the earth, but distributed His gifts over different regions, to the end that men might cultivate a social relationship because one would have need of the help of another. And so He called commerce into being, that all men might be able to have common enjoyment of the fruits of the earth, no matter where produced."

-Libanius (AD 314-393), Orations (III)

3

Today's Environment

- Declining Resources (with great "uncertainty")
- Rising Costs (labor, equipment, energy, health, etc.)
- Demographics and debt payments adverse to needs
- Rapidly Changing World (technology, economics, geopolitics, etc.)
- Globalization a reality (industry, technology, economics, labor, and security)
- Broad spectrum of security concerns (pirates, terrorists, cyber, chemical bio, nuclear proliferation, "road-side bombs," regional instabilities, etc.) - - with great "uncertainty"(both in scenarios and in funding)

4

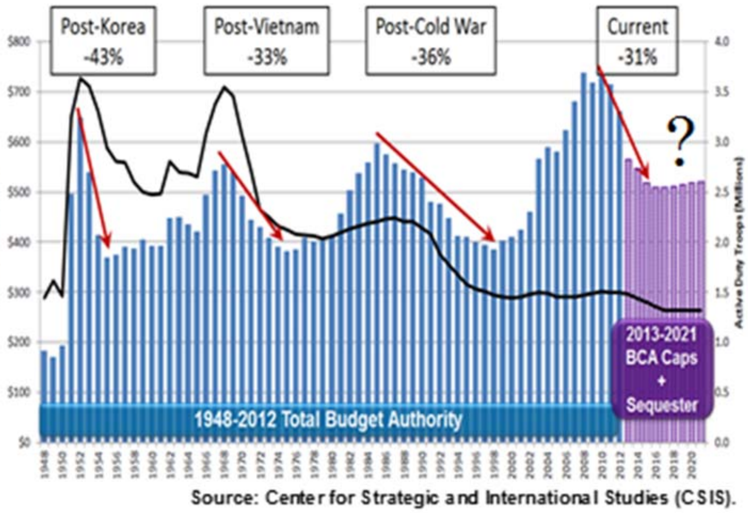
The Message

- In General: Today, industry, technology, and labor are Globalized - - but, U.S. defense industrial-based policies are **not**!
- All Future Security Scenarios are likely to be multi-nation; requiring combined-force interoperability - - but U.S. export controls largely limit this.
- In many areas today, the U.S. is no longer the technological leader - - but "buy America" and other import controls, limit our acquisitions; yet our National Security strategy is "technological superiority."

U.S. Defense Industrial Strategy/Policy **Must Change;** In Order to Gain the **Economic and Security Benefits of Globalization.**

5

Likely Shrinking U.S. Defense Budget



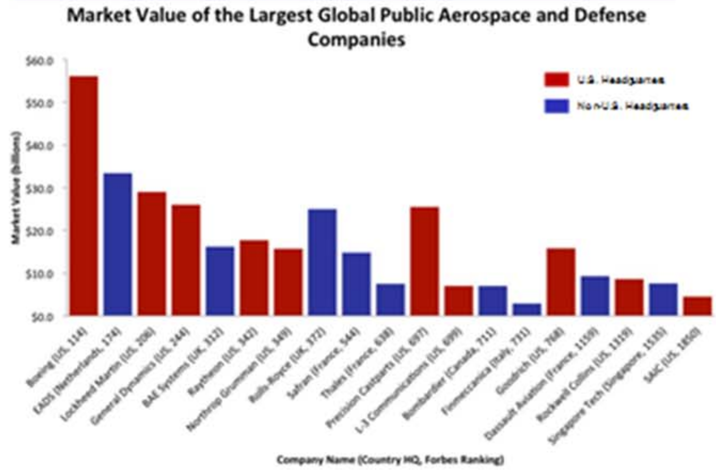
Source: Center for Strategic and International Studies (CSIS).

6


Allies also Resource Constrained
"The economic crisis has hit our defence spending hard," said NATO Secretary General Anders Fogh Rasmussen, addressing the NATO Parliamentary Assembly in Prague. "Compared to 2009, total Allied defence expenditure last year declined by over 56 billion US dollars in real terms" (NATO Press Release, November 2012).
In an era of decreasing defense budgets, the United States and other NATO allies must understand how best to allocate their resources within a global market.
NATO has proposed integrated "Smart Buying" as the best Multinational approach.


Internationalizing the Defense Industrial Base
The defense industrial base of the United States has undergone a sea change in its composition, becoming increasingly reliant on international sources for its development, production, and provision.
Major players in the U. S. defense industrial base are no longer solely domestic.
In 2012, 20 Aerospace and Defense firms made the Forbes Global 2000 List of the largest public companies operating in the global market.

Market Value of the Largest Public Aerospace and Defense Companies



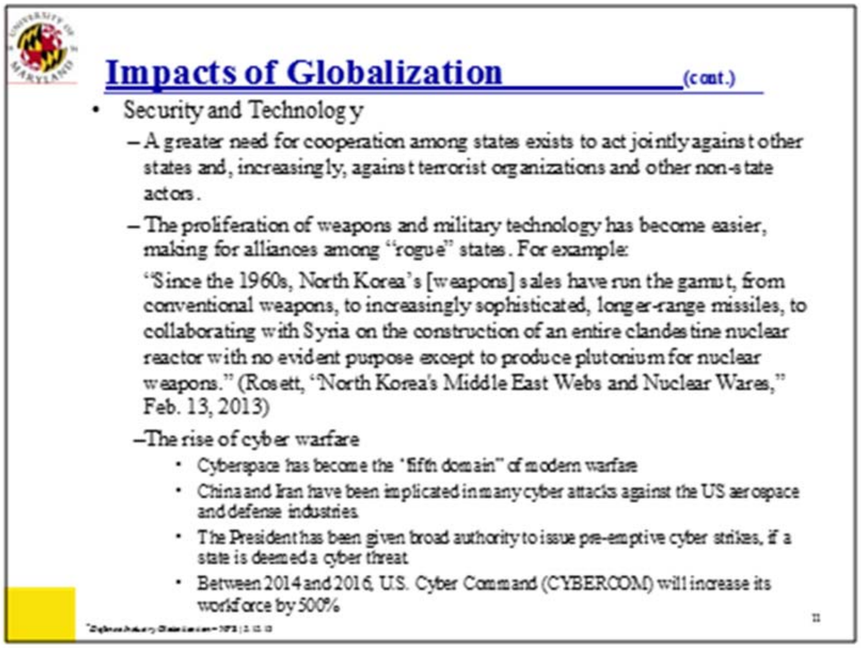
Source: Forbes, "The World's Biggest Public Companies," April 18, 2012, http://www.forbes.com/global2000/

Note: Rankings are based on Sales, Profits, Assets and Market Value

Impacts of Globalization

- **Communication**
  - The advent of new technologies allows for the relatively low-cost and, in many cases, instantaneous, transfer of large amounts of information.
  - Borders are porous and no longer easily enforced.
- **Culture and Education**
  - A complicated global citizenry exists - - Loyalties may be split
  - Foreign nationals are able to travel to the United States and obtain visas to work and attend school - - "brain drain" occurs as these people return to their countries of origin
- **Economic**
  - Firms are increasingly multinational in orientation.
  - Economic alliances and treaties are created to promote mutually beneficial international trade policies for member states.
  - Dual-use technology is made available to the commercial market.
    - e.g., Global Positioning System (GPS), night-vision technology, etc.

Continued →


Impacts of Globalization (cont.)
• Security and Technology
– A greater need for cooperation among states exists to act jointly against other states and, increasingly, against terrorist organizations and other non-state actors.
– The proliferation of weapons and military technology has become easier, making for alliances among "rogue" states. For example:
"Since the 1960s, North Korea's [weapons] sales have run the gamut, from conventional weapons, to increasingly sophisticated, longer-range missiles, to collaborating with Syria on the construction of an entire clandestine nuclear reactor with no evident purpose except to produce plutonium for nuclear weapons." (Rosett, "North Korea's Middle East Webs and Nuclear Wares," Feb. 13, 2013)
– The rise of cyber warfare
• Cyberspace has become the "fifth domain" of modern warfare
• China and Iran have been implicated in many cyber attacks against the US aerospace and defense industries
• The President has been given broad authority to issue pre-emptive cyber strikes, if a state is deemed a cyber threat
• Between 2014 and 2016, U.S. Cyber Command (CYBERCOM) will increase its workforce by 500%
11


Potential Benefits of Strategy/Policy Change
Security:
– U.S. and allies would both have State of the Art ("best in class")
– U.S. and allies' forces would be interoperable (exercises and war)
Economic:
– Economies of scale (from greater volume)
– Greater competition (for best performance at lowest cost)
These Can Be Realized; While Always Directly Addressing Any Potential Security Risks
12

The "Good News"

- In spite of the domestic politics, and "barriers" created, steps are being taken:
  - The MRAP vehicle (designed to harden against roadside bombs) uses armor designed in Israel, shock absorbers from Germany, tires from France, and some Asian electronics
  - All U.S. weapons have some elements originally from foreign sources - - because of their superior performance
  - Many leading, domestically located, U.S. defense firms are majority-foreign-owned (e.g., BAE systems; Finmeccanica; EADS; Thales; Plasan; Serco; etc. - - all with "Special Security" Boards)

President Obama Has Indicated a Willingness to Review Export/Import Controls

Joint Strike Fighter: F-35 Lightning II Program

- The prime contractor of the F-35 program is the American firm Lockheed Martin, with American and British firms, Northrup Grumman and BAE Systems, brought in as principal partners.
- Additionally, eight nations besides the United States are involved in the F-35's 10-year System Development and Demonstration (SDD) phase: the United Kingdom, Italy, the Netherlands, Turkey, Canada, Denmark, Norway and Australia.
- By partnering with the US during System Design and Development, firms in these countries can "bid for work on a best-value basis, and participate in the aircraft's development."
- Israel and Singapore have also agreed to join the program as Security Cooperation Participants.

(Source: "F-35," Joint Strike Fighter, http://www.jsf.mil/f35/.)

The Critical Labor Market

- National Security requires the best in STEM (Science, Technology, Engineering, and Math) - - but U.S. students are not selecting these fields
- Many Top U.S. Universities and U.S. Industry Research Centers are establishing overseas operations
- More than half of the graduate students in many top U.S. Universities, in STEM, are foreign students - - who we "encourage" to return home after their studies (vs. obtain citizenship; if they want it)
- President Reagan decided they can work on government-funded, fundamental research (NSDD-189); but even this has been "discouraged"
- The Executive and Legislative branches are considering increasing the number of visas for STEM immigrants (with advanced degrees)

15

Initial Signs of Change

- Most U.S. and foreign defense firms are now "globalized" - - and the trend is growing
- A DOD "Study on the Impact of Foreign Sourcing of Systems" [OSD, January 2004] concluded: "utilizing foreign sources does not impact long-term readiness; nor impact the economic viability of the national technology and industrial base"
- The U.K. recently had a Navy ship built in South Korea (for "best value"); and the U.S. is competing its Littoral Combat Ship between a U.S firm and an Australian firm.

The Technological, Economic and Security Potential Benefits of Globalization are Slowly Being Recognized; Now the Strategies and Policies Must be Adjusted!

Bottleneck Analysis on the DoD Pre-Milestone B Acquisition Processes

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Abstract

The current Enterprise Requirements and Acquisition Model, a discrete event simulation of the major tasks and decisions within the DoD acquisition system, identifies several what-if intervention strategies to improve program completion time. However, processes that contribute to the program acquisition completion time were not explicitly identified. This research seeks to determine the acquisition processes that contribute significantly to the time a program reaches Milestone (MS) B and provide interventions to improve program completion time. In order to solve this problem, this research uses critical path analysis to determine the bottleneck activities in the Pre-MS B processes using additional simulation analysis. Results show that the systems engineering processes are the bottleneck activities in Pre-MS B acquisition stage. Furthermore, this research then examines the effect of these processes by varying the mean completion times and having them occur earlier in the acquisition process. Potential policies are formulated from the results to further reduce program acquisition completion time.

Introduction

A large number of Department of Defense (DoD) projects are being completed behind schedule and over-budget (Schwartz, 2010). To support this claim, a Government Accountability Office (GAO) report released in 2009 stated that for the DoD's 2008 portfolio, on average a program faced a 22-month delay and exceeded the original budget (Sullivan et al., 2009). Generally, total cost growth of 44% has been consistent over the past few decades with a recent assessment by RAND (Arena et al., 2006). Hence, potential intervention strategies and policies to improve the acquisition processes would be worthwhile. On the other hand, since the end-to-end DoD acquisition process is a large, complex, socio-technological system, it is difficult to analyze and determine which processes or factors affect performance metrics like time, cost, and resource utilization. The current DoD acquisition system, which is composed of three separate and distinct processes—the Joint Capabilities Integration Development System (JCIDS), the Planning, Programming, Budgeting & Execution (PPBE) process, and the formal acquisition development system outlined by the DoD 5000 series of instructions—does not exist in a static environment. The system is constantly being adjusted, either through policy changes or statute (CJCS, 2012; Weapon System Acquisition Reform Act of 2009; OUSD[AT&L], 2008). Hence, other viable analysis methodologies must be utilized to fully comprehend this complex system.

In 2009, a discrete event simulation (DES) model called the Enterprise Requirements and Acquisition Model (ERAM) was created by Wirthlin (2009). This model was created to simulate the actual acquisition processes of the DoD, using the Air Force implementation of acquisition processes as the basis of the model, in order to provide further insight and understanding of the complex system's behavior. Furthermore, ERAM has benefited from additional research since the original 2009 Wirthlin version (Leach & Searle, 2011; Montgomery, 2012). These new versions have added additional functionality and options for model users to manipulate (Wirthlin, Houston, & Madachy, 2011). According to the ERAM model, during the acquisition process, approximately 80% of the time, a program was undergoing parallel processes when it is in the acquisition system. It was also observed that one of the main portions of the model during which these parallel processes take place are within the Pre-Milestone B (Pre-MS B) stage. However, Wirthlin's research did not identify the significant processes that affect the total program time for a project to reach MS B.

Against this background, this research addressed these limitations and issues by additional simulation and statistical analysis on the ERAM Arena version of the model. The end goal of this research was to determine the bottleneck of the Pre-MS B processes, investigate interventions to alleviate the bottleneck, and translate them into implementable policy changes. The rest of this paper is organized as follows. The Review of Literature section provides an overview of the current literature on bottleneck analysis and the ERAM model. The Simulation Analysis Methodology section presents the simulation analysis methodology performed, while the Results and Discussions section shows the results of the analysis. Finally, the Conclusions section presents the conclusions of this research as well as viable intervention policies for reducing the time a program takes to reach MS B.

Review of Literature

The ERAM Model

The ERAM simulation model extends from the generation of capability requirements in the JCIDS process to MS C, the review before the production stage begins. Additionally, the ERAM is abstracted at a very high level (Wirthlin, 2009). This high level of abstraction allows overall system performance to be more easily studied. For each replication, ERAM produces schedule time for programs that reach MS C. Although cost is not measured, it

was found that cost overruns were closely related to schedule overruns (Wirthlin, 2009). The validation and verification of ERAM included hand modeling, iterations of correction from feedback of experts in all three systems that comprise the entire acquisition system, and comparison of schedule and budget information from the DAMIR and SMART databases to distributions of the schedule time of model-generated data (Wirthlin, 2009).

The original version of ERAM was created in Arena Simulation software; however, it was translated into an ExtendSim version (ERAM 1.0) to serve as a schedule and success estimation tool of space programs for the Concept Design Center of Aerospace Corporation (Leach & Searle, 2011). Leach and Searle further modified the model introducing ERAM 1.1 to 2.1 by correcting discrepancies between the Arena and ExtendSim models, adding user-controlled variables, incorporating space-acquisition specific elements, and updating the model to include policy in the newly released DoDI 5000.02 document. Montgomery (2012) continued developing the model in order to add the rapid acquisition process and include ACAT II/III programs. A summary of the versions of the ERAM is presented in Table 1.

Table 1. ERAM Versions Adapted From Houston (2012)

Author	Version Number	Changes
Wirthlin (2009)	ERAM 1.0	Baseline Translation from Arena to ExtendSim
Leach and Searle (2011)	ERAM 1.1	Updates by the Aerospace Design Team and Served as new baseline model
	ERAM 1.2	Implemented new DoD 5000.02 policies
	ERAM 2.0	Incorporated the global variables that modify acquisition capabilities
	ERAM 2.1	Incorporated the JCIDS review process
Montgomery (2012)	ERAM 2.2	Added more capabilities for ACAT 2/3 and Rapid Acquisition Process

Since the ExtendSim version of ERAM was designed with the purpose of allowing Aerospace Corporation to create estimates of the schedule and success of a particular project, it has a distinctly different scope and utility from the Arena model of ERAM. The Arena model allows the user to view the behavior of the overall portfolio while the ExtendSim version allows the user to investigate a specific program. For example, while the ExtendSim requires the user to select a specific ACAT level for the program being tested, the Arena version assigns ACAT levels based on the distribution of programs observed in the actual acquisition system. While the ExtendSim version of ERAM was designed with the intention of allowing the user to perform what-if scenarios, as far as the researcher is concerned, no literature of the evaluation of possible intervention strategies using the ExtendSim version of ERAM has been published. In his dissertation, Wirthlin investigated the effect of 20 interventions on the effect of end-to-end acquisition time in the Arena version. When all 20 interventions were implemented, a 20% reduction in end-to-end acquisition time was achieved. However, more interventions can be developed to further study and improve the DoD end-to-end acquisition process.

Critical Path Analysis

To the best of our knowledge, no literature has attempted to identify the critical path of the acquisition process (Monaco & White, 2005). Although long cycle times continue to

plague DoD acquisition programs, relatively few studies have focused on identifying significant processes that dictate program cycle time. Despite the Packard Commission's assertion that schedule drives costs, most studies and policy changes have focused on cost reduction rather than reducing cycle time (Al-Harbi, 2001; McNutt, 1999). Drezner and Smith (1990) performed a statistical analysis of 10 programs in order to hypothesize factors that affect the original plan and program deviation. A study performed by Tyson, Nelson, Om, and Palmer (1989) examined schedule variance and its causes. The study found that prototyping, sole-source procurement, fixed-priced contracts, and multiyear procurement reduced schedule variance. The study also found that programs awarded through full and open competition experience more schedule growth than those programs that did not. Another possible schedule driver is presented by Brown, Flowe, and Hamel (2007). Brown et al. compared the schedule quality of joint and single-system programs. From this study it was found that joint system programs have significantly more schedule breaches; however, the research did not identify the root cause of this difference (Brown et al., 2007).

In summary, to the best of our knowledge, there exists no research that has been conducted that isolates and identifies bottleneck activities and its effect on the program completion time throughout the DoD acquisition process. Hence, intervention strategies to be developed must be focused on addressing bottleneck issues to obtain maximum improvement of the end-to-end DoD acquisition process.

Simulation Analysis Methodology

This section describes the analysis performed to identify bottleneck operations within the Pre-MS B stage. After identifying bottleneck operations, intervention strategies were also formulated in this section to reduce total program completion time. Hence, this research was performed in two phases. A brief description of these phases is presented as follows:

- The first phase performed a critical path analysis on the Pre-MS B activities to identify a bottleneck (see the Identification of Bottleneck Activities subsection).
- The second phase focused on investigating the effect of reducing the process times of the identified bottleneck activities from Phase 1 and determining the effect of allowing them to be executed earlier in the process (see the Design of Pre-MS B Bottleneck Interventions subsection).

Identification of Bottleneck Activities

In order to perform critical path analysis, the Pre-MS B section was mapped by hand to assist in visualization of the complex network of separation and batches in the acquisition system. The processes between each Separate and Batch method were left out for simplicity and ease of interpretation. The section or line segment between any two nodes was labeled. Figure 1 shows the mapped version of the Pre-MS B activities and Table 2 shows the activities associated with each section.

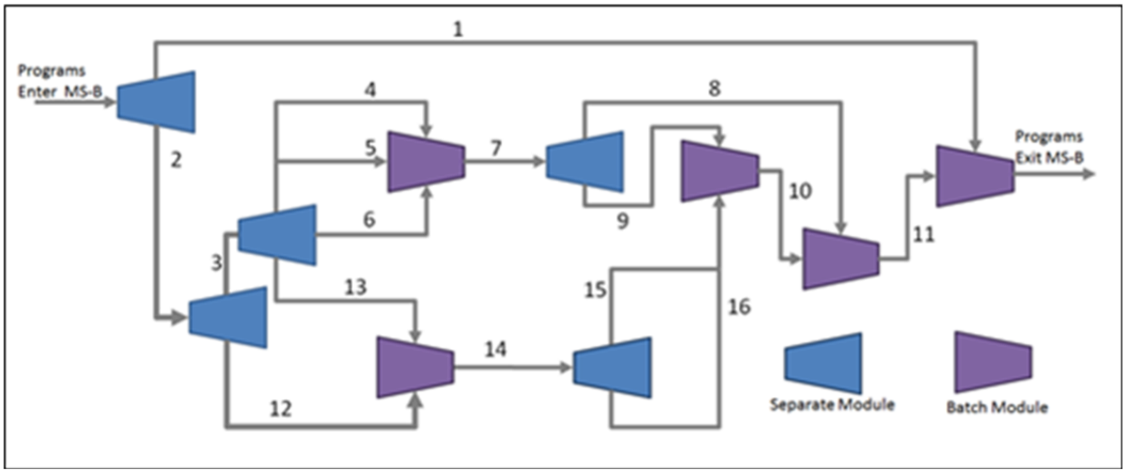

Figure 1. Pre-MS B Flowchart

Table 2. List of Activities in the Pre-MS B Flowchart

Section	Description of Activities
1	Requirements generation: KPP Development, high performance team work, etc.
2	RFP release, contract awarding
3	Waiting period for start of contract
4-6	Cost estimates (contractor, program office, and independent)
7	Affordability assessment
8	Set acquisition program baseline
9-10	No processes
11	Prepare and conduct acquisition panels
12	Early Systems Engineering (SE) activities: EOA, developmental testing, SRR, etc.
13	Acquisition planning activities
14	Draft RFP
15	RFP coordination
16	Source selection plans

Several Assign and Record modules were added to the Arena model in order to determine the time to complete each segment. Next, a trial of 3,000 runs was performed in Arena, and the times for each segment were collected. A spreadsheet was then used to analyze results and to determine the time of every possible path from the beginning of the Pre-MS B activities to the MS B decision. The path that took the longest amount of time was deemed as the critical path. By comparing segments in the longest paths to the sections found in shorter paths, the bottleneck activities for the Pre-MS B processes were identified.

Design of Pre-MS B Bottleneck Interventions

In order to improve the performance and alleviate the delay caused by this bottleneck, two intervention strategies were developed and tested in ERAM. The first intervention performed was to test the effect of decreasing the process time for all bottleneck activities. In order to test the effect of reducing total process time, the minimum, maximum, and mode for these activities was reduced by a fixed percentage. A paired t-test was then performed to compare each trial to the baseline at 95% confidence level. The reduction by using a fixed percentage was performed until a statistically significant change was obtained. Furthermore, the second intervention was a sensitivity analysis to determine the effect of allowing the bottleneck to be performed earlier in the Pre-MS B process to determine its effect on the total process time. The results of these interventions are illustrated in the next section.

Results and Discussions

This section presents the results of both simulation analysis phases performed on the ERAM Arena model. Specifically, the Pre-MS B Critical Path Analysis Results subsection presents the results of the identification of the critical path and bottleneck activities. Additionally, the Additional Pre-MS B Bottleneck Interventions subsection shows the results of the interventions performed on the bottleneck analysis to improve program completion time.

Pre-MS B Critical Path Analysis Results

During the critical path analysis, times for all 11 paths through the system were calculated. The paths were labeled by letters. Each path was composed of segments. A subset of the paths and their corresponding activities is shown in Table 3.

Table 3. List of Paths and Segments for Pre-MS B

Path Name	Corresponding Segments From Figure 1
A	1
B	2, 12, 14, 16, 10, 11
C	2, 12, 14, 15, 10, 11
D	2, 3, 6, 7, 8, 11
E	2, 3, 5, 7, 8, 11
F	2, 3, 4, 7, 8, 11
G	2, 3, 6, 7, 9, 10, 11
H	2, 3, 5, 7, 9, 10, 11
I	2, 3, 4, 7, 9, 10, 11
J	2, 3, 13, 14, 15, 10, 11
K	2, 3, 13, 14, 16, 10, 11

As seen from the Table 3, paths B and C heavily overlap while path A has no overlap with any other path. From the total time for each path, the longest was deemed the critical path. The second longest and third longest paths were also determined. A subset of this data can be seen in Table 4.

Table 4. Length of Longest Paths to MS B

Run	Percentage of Runs as Longest Path	Percentage of Runs as Second Longest Path	Percentage of Runs as Third Longest Path	Percentage of Runs in the Top Three Longest Path
A	45	8.75	42.5	96.25
B	43.75	38.75	7.5	90.00
C	6.25	38.75	31.25	76.25
D	3.75	8.75	8.75	21.25
F	0	2.5	5	7.5
J	0	1.25	1.25	2.50
K	1.25	1.25	3.75	6.25
E, G, H, I	0	0	0	0

As can be observed in Table 4, the critical path was most often A, B, and C. In approximately 95% of the trials, either A, B, or C composed the critical path. Specifically, 50% of the time path B or C was the critical path, and 45% of the time path A was the critical path. We note that path B and C have significant overlap; therefore, they are considered as a single path, path B/C. Since the critical path was very evenly split between path A and path B/C, it can be deduced that a Pre-MS B process common to both of paths would be the bottleneck of the process.

In examining the ERAM, it can be gleaned that there was some interaction between path A and path B/C. One of the last modules of path A was a hold module called “Wait for EOA completion.” A screenshot of this module can be seen in Figure 2.

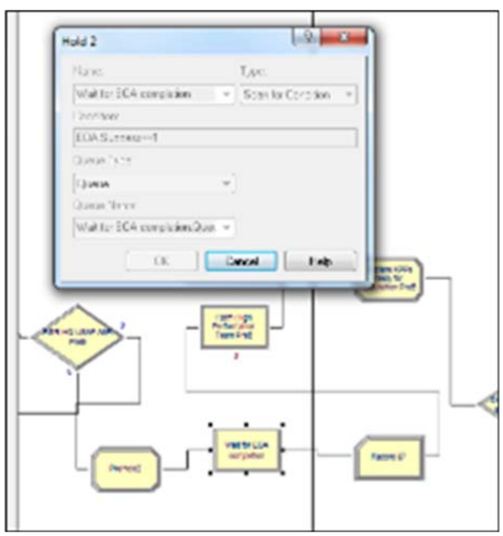

Figure 2. Wait for EOA Completion Screenshot

As seen in Figure 2, path A must wait for the EOA to be complete before the path can finish. A second communication occurs between the two paths. In order for the SE activities, like the EOA, to occur, the Key Performance Parameters (KPPs) must be

complete. The hold model called “Wait for T&E start” facilitates this communication and can be seen in Figure 3.

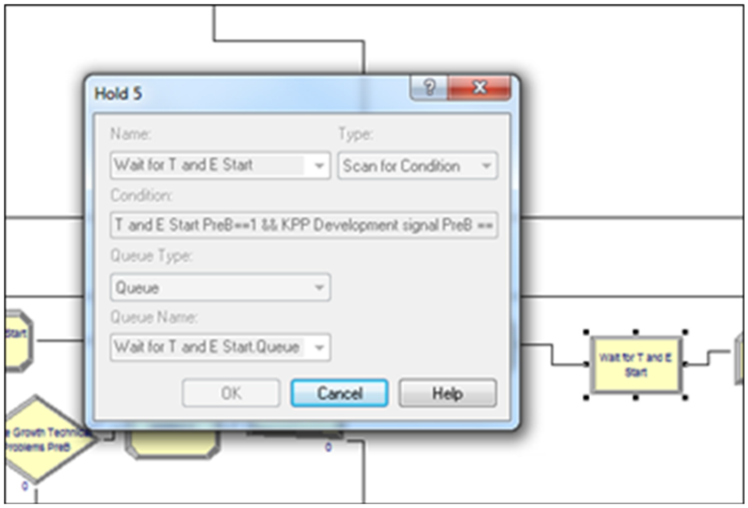

Figure 3. Wait for T&E start Screenshot

However, we note that this hold module also waits for the 75% of the contract length to elapse. At the default settings, the KPPs will always be completed in less than 75% of the contract length. Therefore, at the default settings, this hold does not serve as communication between the paths.

Since the completion of the EOA was the only communication between the two critical paths, the SE activities that begin before the EOA completion was determined to be the bottleneck of the Pre-MS B activities. If this bottleneck activity were removed, the time to MS B would be reduced by an average of 6.8%.

Additional Pre-MS B Bottleneck Interventions

Table 5 summarizes the results of the t-tests performed for when the process time for MS B system engineering activities was reduced. The tables show a subset of trials corresponding to a reduction in process times by 0%, 20%, 35%, or 50%. These settings were selected to show the sensitivity of the model to various degrees of process time reduction. From these simulation analyses, the mean ($\mu_{i^{th}\%}$) and standard deviation of the total completion time for each trial were calculated. These calculated means were compared to the mean of the baseline setting (μ_{base}) in the default settings, or 0% process time reduction. The null hypothesis for the t-tests is $H_0: \mu_{base} = \mu_{i^{th}\%}$ which corresponds to a failure to reject the claim that the baseline and the i^{th} percentage are similar and alternative hypothesis $H_1: \mu_{base} \neq \mu_{i^{th}\%}$ if there is significant difference.

Table 5. Summary of t-Test Results of Process Time Reduction for SE Activities

	% Reduction of Process Time			
	0% (Baseline)	20%	35%	50%
Average Time to MS B (Days)	3418.01	3274.90	3211.564	3164.25
Standard Deviation (Days)	1701.08	1636.108	1557.816	1515.48
P-Value		0.281	0.109	0.046
Conclusion		Fail to Reject H_0	Fail to Reject H_0	Reject H_0

As seen in Table 5, it is evident that when the process time for SE activities was decreased by less than 50%, there will not be a statistically significant decrease in the time to MS B. However, when the process times for SE activities are reduced by more than approximately 50%, the model exhibits a statistically significant decrease in time to MS B.

Based on the identified bottleneck, which was the SE activities, a second intervention was developed. Specifically a sensitivity analysis was done to test the effect of allowing the bottleneck activities to occur earlier in the contract. This was implemented by adjusting the module called “Begin Testing PreB,” which can be seen in Figure 4.

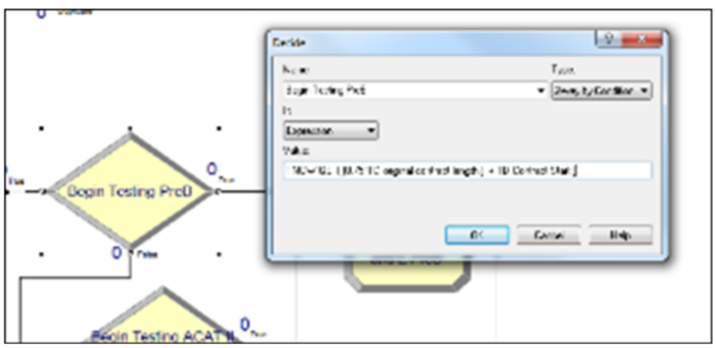

Figure 4. Begin Testing PreB Screenshot

The “Begin Testing PreB” module is a Decide module that, when set to true, triggers the beginning of the SE activities. The original criteria for the decide module, as verified and validated by Wirthlin when creating the ERAM model, was that 75% of the contract length must pass before these activities can occur. During this research, this percent was decreased to simulate the SE activities occurring sooner and more resources being applied at the beginning of the contract.

In addition, to allow SE tasks to begin sooner, the KPPs must be completed sooner in the process as their completion is also needed to trigger the start of the SE tasks. A more complete discussion of this interaction can be found in the Pre-MS B Critical Path Analysis Results subsection. The process time of the KPP development was reduced in order for the KPPs to be completed in a manner that does not delay the SE activities. A paired t-test was then performed to compare each trial to the baseline at 95% confidence level.

Tables 6 and Table 7 summarize the results of the t-tests performed for allowing Pre-MS B contractor activities to occur earlier in the contract. Specifically, Table 6 shows the effect of allowing the SE activities to occur earlier in the contract when the KPPs generation process time was not decreased, and Table 7 shows the effect of allowing the SE activities to occur earlier in the contract in conjunction with the KPPs generation process performing faster. Table 6 shows a subset of trials corresponding to the SE activity starting when 75%, 50%, 33%, or 25% of the contract has elapsed. Table 7 shows a subset of trials corresponding to the SE activity starting when 75%, 65%, 60%, or 55% of the contract has elapsed.

These settings were selected to show the sensitivity of the model to various start times of SE activities. From these simulations, the mean ($\mu_{i^{th}\%}$) and standard deviation of the total MS B completion time for each trial were calculated. These calculated means were compared to the mean of the baseline setting (μ_{base}) in the default settings, or starting after 75% of the contract has elapsed. The null hypothesis for the t-tests is $H_0\colon \mu_{base} = \mu_{i^{th}\%}$ which corresponds to a failure to reject the claim that the baseline and the i^{th} percentage of contract elapsing before start is similar in terms of program completion time and alternative hypothesis $H_1\colon \mu_{base} \neq \mu_{i^{th}\%}$ if there is significant difference.

Table 6. Summary of t-Test Results of SE Activity Start Time Adjustments With Original KPP's Process Time

	% of Contract Elapsed Before Start			
	75% (Baseline)	50%	33%	25%
Average Time to MS B (Days)	3418.01	3379.09	3379.09	3379.09
Standard Deviation (Days)	1701.08	1670.31	1670.31	1670.31
P-Value		0.770	0.770	0.770
Conclusion		Fail to Reject H_0	Fail to Reject H_0	Fail to Reject H_0

Table 7. Summary of t-Test Results of SE Activity Start Time Adjustments With Reduced KPP's Process Time

	% of Contract Elapsed Before Start			
	75% (Baseline)	65%	60%	55%
Average Time to MS B (Days)	3418.01	3305.44	3200.75	3139.95
Standard Deviation (Days)	1701.08	1628.08	1599.04	1553.38
P-Value		0.392	0.099	0.032
Conclusion		Fail to Reject H_0	Fail to Reject H_0	Reject H_0

As seen in Table 6, it is evident that the time to MS B is not sensitive to an earlier start time for SE activities when the KPP process time is set to the default distribution. In fact, when the start time is at 50%, 33%, and 25% of the contract time, the time to MS B, standard deviation of time to MS B, and p-value are identical. This is due to the hold module in the SE path described earlier. As previously discussed, in order for the SE activities to begin, a percent of the contract must elapse and the KPPs must be complete. Once the SE activities start time occurs earlier than 50% of the contract length, the KPPs completion is the determining factor of the SE activity start time.

Table 7 takes this into account by reducing the KPPs' process time to a point where it does not dictate the start of the SE activities. As seen in Table 7, it is evident that when SE activities begin at 60% of the contract length or later, there will not be a statistically significant decrease in the time to MS B. However, when SE activities begin at 55% of the contract length or sooner and the KPPs' generation processes are shortened to the same degree, the model exhibits a statistically significant decrease in time to MS B.

Conclusions

The critical path analysis performed in this research indicated that the SE activities and their communication with the requirements branch are the bottleneck of the Pre-MS B portion of the acquisition system. In addition, the research indicated that focusing on reforms that address this bottleneck has the potential to decrease the total time spent on MS B activities by approximately 7%; this corresponds to a process time reduction of approximately six months.

This research also tested two strategies to address this bottleneck. The first was reducing the process time of all SE activities. The second was to allow the SE activities to have an earlier start time. This research showed that the latter policy has the potential to be the most beneficial. This research showed that the process times for all SE activities must be decreased by approximately 50% in order for a statistically significant decrease in time to MS B to occur. This degree of process time reduction may be infeasible. On the other hand, allowing the SE activities to occur after 55% of the contract time has elapsed rather than the current 75% produces a statistically significant decrease in time to MS B.

The increased sensitivity of program time to start time, rather than process length, suggests that schedule benefits may be achieved if the some resources, both financial and human, are transferred from the SE activities to the activities prior to test and development. However, this re-allocation of resources must be accompanied by responsiveness from the JCIDS branch, which is the branch that generates the KPPs. This research indicates that there was a large amount of co-dependence between the JCIDS and SE activities and that communication and coordination between these branches is needed in order to address the bottleneck.

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Disclaimer

Software Acquisition Patterns of Failure and How to Recognize Them[1]

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Abstract

In systems today, software provides substantial portions of capability and performance. In many Department of Defense (DoD) acquisitions, however, software too often is a minor consideration when the early and most constraining decisions about program cost, schedule, and behavior are made (i.e., prior to Milestone A). These decisions manifest themselves in the acquisition strategy, the system and software architecture, and ultimately in the deployed

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system. Based on our experience with large programs, we have identified seven patterns of failure that lead to misalignment between the software architecture and the acquisition strategy, leading to program restarts, cancellations, or other failures.

We describe the characteristics of these patterns of failure and relate them to weak or missing relationships between key artifacts—relationships that should exist even at an early stage of the life cycle. In this paper, we focus on those artifacts that relate to the expression and analysis of business goals. We present early results in the development of acquisition quality attributes (analogous to software quality attributes) and how these attributes relate to acquisition strategies. We conclude with some speculation on what is needed to avoid the failure patterns.

Introduction

In systems today, software provides substantial portions of capability and performance. One consequence for DoD acquisition is that software issues are major factors in cost and schedule overruns. However, software is often a minor consideration when the early, most constraining program decisions are made. This has negative consequences, most often in terms of *misalignments* between the software architecture[2] and system acquisition strategies.[3] Our analysis of troubled programs shows that these misalignments lead to program restarts, cancellations, and failure to meet important mission and business goals.[4] Our research focuses on enabling organizations to reduce their program failures by harmonizing their acquisition strategy with their system and software architectures.

One major source of misalignments is the diverse sets of stakeholders of complex programs; it is inevitable that some (perhaps many) of their diverse goals and priorities are in conflict. Operational users, combat commanders, funding authorities, and acquisition team members may think they share the same priorities, but when interviewed, their answers often vary widely in terms of the goals and features they see as the most important. In many cases, the solutions that are then created are based on goals of one set of stakeholders—goals that can conflict with those of other stakeholders without explicit consideration of the tradeoffs being made. Ultimately, such conflicts in goals eventuate in the misalignments described previously.

Observed Patterns of Failure

Characteristics of the Patterns We Observed

The major source of our data for this research was interviews with participants in major acquisition programs, most of which encountered some sort of difficulty, ranging from partial to total failure. These data are also supported by decades of experience on the part of all of the authors in studying, assessing, and participating in actual programs, many of which evidenced similar failing behaviors. Virtually all of the conclusions derived from our

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[2] *Software architecture* is defined by Bass, Clements, and Kazman (2012) as “the structure or structures of the system, which comprise software elements, the externally visible properties of those elements, and the relationships among them.”

[3] *Acquisition strategy* (2011) is defined by the Defense Acquisition University as “a business and technical management approach designed to achieve program objectives within the resource constraints imposed. It is the framework for planning, directing, contracting for, and managing a program. It provides a master schedule for research, development, test, production, fielding, modification, postproduction management, and other activities essential for program success.”

[4] A mission goal is an expression of an objective that affects a user, focused on what the solution or product should do or how it should behave. A business goal is an expression of an organizational (e.g., Navy) objective, focused on goals relative to the business model for acquiring or developing the solution or product.

interviews were strongly supported by our aggregate experiences as active professionals, in both government and non-government roles in the domain of DoD acquisition. Analysis of these data has led us to observe several recurring patterns. Because of their negative consequences, and following common usage throughout the software engineering community as exemplified by Brown, Malveau, McCormick, and Mowbray (1998), we characterize these as *anti-patterns*.

Buschmann, Meunier, Rohnert, Sommerlad, and Stal (1996) provided a form for describing patterns, calling out the need to give patterns a name and to define the context (environment), the problem, and the solution. We modify this approach for our anti-pattern descriptions. First, we include the notion of consequence, as defined by Gamma, Helm, Johnson, and Vlissides (1994). Second, in lieu of calling the observed activity “solution,” we have titled that activity “observed response” (i.e., to the problem). Thus, each of our anti-pattern descriptions has the following elements:

- name (readily identifies some key aspect of the problem)
- context (situations where the pattern occurs)
- problem (recurring issues and forces that characterize the problem)
- observed response (the manner in which people attempt, consciously or otherwise, to solve the problem)
- consequences (results of applying the observed response to the problem in the given context)

Overview of Findings

In each of the programs studied, we observed several instances of activities and behaviors that qualify as anti-patterns. In some cases, the anti-patterns were of sufficient magnitude that they had severe negative effects on program success. None of the anti-patterns were observed in all of the programs we studied, and none were seen in only one program. We, therefore, believe that they were sufficiently pervasive that they were true patterns of behavior.

The set of anti-patterns we observed in these programs consists of the following:

1. Undocumented Business Goals
2. Unresolved Conflicting Goals
3. Failure to Adapt
4. Turbulent Acquisition Environment
5. Poor Consideration of Software
6. Inappropriate Acquisition Strategies
7. Overlooking Quality Attributes

These anti-patterns, like most factors that negatively affect acquisition programs, eventually result in a small number of familiar and unhappy consequences: schedule delays, cost overruns, delivery of less than was promised, or outright program cancellation. In that sense, the *ultimate* consequences of these anti-patterns in the programs we studied have an expected similarity.

However, the *immediate* consequences of different anti-patterns differ in many ways. For example, the immediate effects of leaving key business goals unstated is different from

those that result from a turbulent acquisition environment. Since, in the methods we hope to develop, we intend to focus on some of the immediate and visible symptoms of anti-patterns as a way to minimize or eliminate their negative influence, these immediate consequences are important. Therefore, in the descriptions that follow, we indicate a number of these immediate consequences, although we also mention, wherever possible, the longer term consequences that we observed.

Each of these is discussed in the subsections that follow.

Undocumented Business Goals

Context. This anti-pattern stems from a lack of precise, well-defined, and well-documented business goals for a DoD acquisition, goals that would correspond to the precise, well-defined mission goals usually created for a program. The DoD's business goals are the major driver for an acquisition strategy, which should make some provision for software. But the actual role that the detailed business goals play in the software, particularly its architecture, is often minimal.

Problem. Although business goals obviously influence a program's acquisition strategy, they can also have a strong influence on system and software architecture. This additional influence is seldom recognized, even when it is vital that it should be. Examples of such influence include the following:

- "avoid vendor lock" or "maximize competition" has potentially significant importance when defining software architecture;
- a mandate to employ reuse as much as possible may have a strong negative impact on the software architecture if the software to be reused is itself poorly architected; and
- the goal of a *software* "open architecture" may have a significant impact on the underlying *system* architecture.[5]

Two factors cause this problem. First, at the high level, many business goals are generally expressed only as very broad mandates, and others are not explicitly expressed at all. Second, at the detailed level, there is no useful process for capturing and prioritizing business goals in a program-specific way that is comparable to the Joint Capabilities Integration and Development System (JCIDS) process that supports definition and prioritization of mission goals and their associated requirements.

This anti-pattern is particularly problematic in programs that are building a system that must integrate with other systems (which may themselves be in varying stages of development). While the high-level goal of an integrated system may be explicit, the detailed goals (together with an understanding of needed resources) for the system of systems (SoS) are often left unspecified.

Observed Response to the Problem. The general response to this anti-pattern is that the architect has no other choice, and hence the mission requirements defined by the operational side drive the architecture, which then reflects *only* those mission requirements. Yet, were the detailed business goals available, some, perhaps many, of those business goals might be critical enough to overshadow some of the mission requirements.

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[5] Using Maier (2006), we characterize typical system architectures as compositional (is-a-part-of relationships) and software architectures as more typically layered hierarchies (is-used-by relationships).

An example can be seen in an instance where there might be an implicit but unspecified business goal that favored a highly distributed contractor/subcontractor profile. Lacking awareness of that goal (because it is unstated), a software architect might reasonably design a monolithic architecture to satisfy a mission goal for performance.

Consequences. This anti-pattern was observed in three of the six programs under study. In the program in which it was most visible, a new system with significant new capabilities was needed; a business goal was to replace several systems that were "end-of-life." The acquisition strategy specified a slow, deliberate pace to ensure that the new capability was defined correctly. But ignored in this strategy was the urgent need by users to replace these failing systems as quickly as possible. When the operators and maintainers of the legacy systems became aware of the intended acquisition strategy, they forced a major change in focus for the program. The consequence was a significant delay for the program.

In the other programs where this anti-pattern was observed, the effect was less pronounced. Systems were delivered, although with less functionality than was expected. In all cases, follow-on programs have been started to create the functionality that was originally promised by these programs.

In sum, the overall effect of this anti-pattern is that important guiding documents—in particular, the architecture and acquisition strategy, or both—fail to reflect the *joint* influence of both business and mission goals. Inevitably, the lack of documentation of missing business-related goals (and their associated quality attributes for the architecture) will result in a system that fails to meet the expectations of at least some of the key stakeholders, because the joint expectations of *all* of the stakeholders have never been adequately reasoned about.

Unresolved Conflicting Goals

Context. This anti-pattern is often a direct consequence of the previous one, the distinction being that the first anti-pattern refers to the *absence* of well-documented business goals, while this one refers to the *lack of an analysis and de-confliction* of the known goals.

Problem. The variety and scope of mission and business goals can be very large, and for a program of any consequence, there will likely be conflicts among some of these diverse goals and priorities. One factor that compounds the problem is that the business goals and the mission goals are often developed by people from different communities—people with very different concerns.

But to reason about these conflicts requires that all of these goals be considered jointly, so that their mutual influence can be understood and misalignments negotiated. Reasoning is obviously impossible if, as in the previous anti-pattern, the business goals are not well documented. But even if there is a set of well-documented business goals, no processes or criteria exist by which tradeoffs between important business and mission goals can be made. It is often not even clear who should arbitrate such goal conflicts.

A frequently observed example of this anti-pattern is reflected in the conflict between the goal of introducing a new or updated system and the additional goal of avoiding impacting how current end users perform their tasks. At best, this is a conflict of expectations that is not fully understood until the system is deployed, potentially presenting a barrier to deployment.

Finally, one specific problem that is often observed, and one that mixes both business and mission elements, is that a program shares dependencies with other systems in a larger SoS context. Too often, each of these systems is considered in isolation, and the mission and business effects that each program should have on the others is ignored. When

these effects surface, joint consideration is often carried out too late in program execution to be effective or to succeed.

Observed Response to the Problem. Program personnel tend to separate into business (e.g., acquisition strategy) and mission (e.g., system and software architecture) communities, each of which tends to work in isolation. Given this separation, these personnel tend to produce artifacts that reflect the goals and priorities known to them; these in turn may be misaligned in that they reflect unresolved conflicts between business and mission goals such as those described previously.

Consequences. This anti-pattern was observed in five of the six programs under study. In one program, various business goals concerning reuse, using multiple contractors, reducing integration costs, and such mission goals as greatly increased performance had produced numerous unresolved conflicts. When the gravity of the conflicts was belatedly understood (by an independent "tiger team"), both the initial acquisition strategy and the initial architecture were abandoned, and a major reconsideration of both—in which they would be reconciled and aligned—was begun. While this brought about a significant delay, it avoided the far worse result of a system that failed both its business and mission stakeholders.

In general, it is likely that in a program of any consequence, conflicts between business and mission goals will exist. But if the conflicts are not reconciled before the acquisition strategy and the architecture (both system and software) are defined, the negative effects that these conflicts will have will be large. Unless *joint* consideration of mission and business goals is carried out early in program execution, conflicts between goals will soon become difficult, or even impossible, to reconcile. And, ultimately, stakeholders who expected their mission or business goals to be reflected in the acquisition strategy and then satisfied by the software architecture are unhappily surprised when the system cannot support their mission or business objectives.

Failure to Adapt

Context. This anti-pattern often occurs when program duration is very long. The reasons for length can be inherent, such as when a system is unprecedented and requires considerable time to solve massive engineering problems (for instance, creation of the Joint Strike Fighter). Or the reasons for highly extended program duration can be circumstantial, such as a protracted, complex protest to a contract award. This anti-pattern can also occur when a program evolves from providing limited capabilities to providing a much wider range of capabilities.

Problem. In most programs, both the acquisition strategy and the architecture are optimized to meet the goals and priorities that exist at the start of the program. However, goals and priorities naturally evolve over time: Examples of such change could include the need to combat new and unexpected threats, or a desire to modernize a capability using new technology. The essential problem lies in the fact that the architecture and acquisition strategy that are initially defined may not be flexible enough to respond to these changes without a good amount of revision and redefinition.

Further, and compounding the problem, there are no widely applicable processes for rapidly revising acquisition strategy for changed business goals, nor are there widely used processes to accommodate changes to architecture as a result of such changed goals.

Observed Response to the Problem. When such changes as those described previously occur, program personnel are often unsure about whether the architecture, acquisition strategy, or both can accommodate the needed changes and, even if they can,

whether the changes can be accomplished, given the time and effort that will be required (e.g., to get all necessary approvals for a revised acquisition strategy). Hence, programs tend to continue executing as though there has been minimal change to the initial goals and priorities; there is little impetus to revise the acquisition strategy or make anything more than minimal alterations to the architecture. In effect, the program is operating with either an implicit change in acquisition strategy or a mismatch between the architecture defined initially and the changed mission goals, or both.

Consequences. In one of the programs we studied, this anti-pattern had a considerable negative effect. The program initially had a very successful architecture and acquisition strategy; the program was so successful that its scope grew from delivering capability for one system to delivering capability to multiple systems of a similar type. The architecture and acquisition strategy survived this change in scope initially, but as the separate systems matured, and as need arose for them to interoperate, unexpected demands were placed on the architecture. An additional factor was that the stakeholders became increasingly interested in system reliability—a new quality attribute for this program. At this point, both the architecture and the acquisition strategy failed. This program has entered a strategic pause while the architecture and the acquisition strategy are reconsidered in light of both the new requirement (reliability) and the increased complexity of what is now a SoS.

In general, this anti-pattern reflects a natural tendency to stay the course, even when circumstances change and external conditions evolve.

Turbulent Acquisition Environment

Context. This anti-pattern is closely related to anti-pattern #3 (Failure to Adapt). But in this case, the cause is not extended program evolution but rather severe instability in multiple program elements. This instability is manifest by changes in goals, strategy, or architecture that are so frequent and contradictory, they require adaptation that, even under the best circumstances, the program is unable to accommodate. These changes can be political, strategic, technological, or fiscal.

Problem. Several causes can bring about program turbulence. Budgets can undergo major revisions, and major portions of a program's funding can be withdrawn. Mission circumstances can be suddenly changed, or radically new technologies can be disseminated rapidly. Programs, particularly if they are perceived to be in severe difficulty, can face significant revisions of goals and purpose. Joint programs often undergo periodic management shifts when different services assume primary responsibility.

In cases where one or more of the previously mentioned conditions are present, a program can find itself faced with the demand for change that is impossible to accommodate. The magnitude of the requested change is often unrealistic, impractical, or impossible, given time and resource realities.

As the program personnel attempt to adapt to the changes, the original architecture and acquisition strategy may now be highly unsuited to the changed conditions that have been levied on the program. The program falls into a mode of "architecture of the day" or "acquisition strategy of the day." Equally problematic and an important part of the problem is that the program is usually still contractually held to some part of the original acquisition strategy.

Observed Response to the Problem. The frequent and significant changes in mission or business goals overpower the ability of the acquisition strategy or architecture (or both) to accommodate them. Thus, the original acquisition strategy is implicitly abandoned

but without having a well-defined new strategy created. Or the architecture is stretched to the breaking point and loses all relation to the original acquisition strategy.

Yet many programs attempt to continue executing with, at most, minimal explicit revision of the acquisition strategy and/or architecture. The necessary task to revise the acquisition strategy to fully account for the changed goals is seldom performed, nor is the work needed to revise the original architecture carried out as carefully as is required.

Consequences. This anti-pattern was observed in three of the six programs under study. In one of them, significant changes to mission, architecture, hardware, and program direction each occurred, some repeatedly. For instance, the program began with a strong research basis but very quickly was given mandates to field equipment as quickly as possible. Different quality attributes were given different priorities as the architecture evolved through several iterations of development. Different contractors were given conflicting priorities throughout program execution. The result was that the program fielded a small fraction of what was originally planned, after which the program was cancelled.

There is little doubt that the environment of DoD acquisition always has some instability; that is the natural condition of government programs. But in the final analysis, when the environment is truly turbulent (i.e., when this anti-pattern is strongly present), the best result is likely to be systems that are poorly fitted to the purposes for which they are to be used. In the worst case, they may even be unfit for use at all.

Poor Consideration of Software

Context. This anti-pattern occurs when critical decisions are made, especially early in a program, that have strong negative implications on the system's software. There is a historical basis for this behavior: For decades, the DoD acquired systems that were primarily hardware. But while the role and importance of software has grown significantly in recent years, the traditions and habits of acquisition still reflect the earlier, hardware-centric posture.

Problem. Very often, software is not deemed a critical factor in decisions made at the earliest stages of a program. These decisions generally are made with little or no understanding of how software must be accounted for in the acquisition strategy or the architecture (or both).

One symptom: Contracts are organized based primarily on the system architecture and fail to take into consideration the very sizable role of software. Assumptions are made about the expected integration of software entities that are created separately; such assumptions are often made with no understanding of the difficulties that arise when complex independent software systems must interoperate or be integrated. This leads to system architectures and acquisition strategies that over-constrain the yet-to-be-defined software architecture, thus adding significant complexity to software development and integration. Even in a software-only system, the real difficulties that the software can pose (e.g., integration of many heterogeneous components) are largely ignored.

One other such symptom is that quality attributes that are important to the system engineering community may be quite different from those that are significant to the software community. Even if the two communities speak of a single quality attribute (e.g., reliability), they refer to different things. Thus, early decisions about quality attributes typically are decisions about system, not software, quality attributes.

Observed Response to the Problem. As a result, the acquisition strategy either is created with a strong focus on system architecture or, in software-only systems, fails to address the software architecture satisfactorily. In the former case, this inevitably produces

a large gap between the system and software architectures; in the latter case, the planned software acquisition strategy is unrealistic and impractical.

A common "solution" is that the software architect tries to play "catch up" and fit the software to the system architecture. Another "solution" is to ignore the eventual complexities of integration and expect that they can be resolved later. In these cases, the result is often that the system constraints force software choices that are suboptimal for the whole system.

Consequence. This anti-pattern was observed in three programs. In one program, two critical early decisions about software were made with very little understanding of software's inherent complexity. The system was large and complex, with three major software components. An early decision concerning the integration of those three components downplayed all of the details of that integration: who would do it, what resources it would need, and how difficult it would be. No attempt was made to base this decision on expert software advice, nor on data readily available from comparable programs about the difficulty of such a task. Another decision related to the assumption that the system could later be made to interoperate with another complex software system. But no rigorous assessment was made of the difficulty of accomplishing that interoperation nor of the resources that this integration would require. In both cases, the assumptions proved false, and the program was cancelled.

In general, in the presence of this anti-pattern, there will be major software requirements that cannot be satisfied. In a system with both hardware and software elements, this is often a direct result of a software architecture that had to be made to fit poorly into a system architecture that was already defined. Further, the problems and delays that result from the gap between the system and the software architectures are typically blamed on the software components alone. In the worst cases, these suboptimal decisions are reflected in system-level schedule delays and cost overruns.

Inappropriate Acquisition Strategies

Context. The time factor figures prominently in DoD acquisitions. Starting from the earliest moments of a program (i.e., the awareness of a need for a new or updated system), one urgent, yet often unstated, imperative is to move quickly to avoid any eventualities that might delay, or even prevent, a program from achieving its desired milestones. This imperative is often exacerbated by the need to spend an amount of money that was established as many as two years previously, at a point where little was actually known about the realities that the program would face. It is further exacerbated by the lengthy review process before a new contract can be awarded. These realities of the time factor have led to acquisition strategies that are often poorly suited to an individual program's needs.

Problem. There are multiple causes of this anti-pattern. Program offices might

- wish to avoid protests
- get quick approval for a program (e.g., before anticipated budget cuts)
- lack sufficient acquisition expertise to develop an acquisition strategy that will quickly gain approval
- have a particular acquisition strategy imposed by a higher authority

In another scenario, some key business goals (e.g., split an acquisition that is conceptually a single system into multiple acquisitions to avoid a "big bang") are in direct conflict with the technology to be used, the system to be built, or both.

Note that these causes can be either external (protests, budget cuts) or internal (inexperience of a program management office to develop and defend a solid acquisition strategy).

Observed Response to the Problem. Whatever the particular cause, the result is that the primary goal of the program office and the source selection team is to get through a competition and issue a contract as quickly as possible. And even though the chosen acquisition strategy might have a poor fit, or even a misfit, with the business and/or mission goals for the system, the inappropriate acquisition strategy is put in place. The program begins execution, deferring or ignoring the parts of the strategy that have a poor fit with the real needs of the system to be built and, too often, the wrong contract relationship with the software developer(s).

Consequences. This anti-pattern was observed in five of the six programs under study. In one program, the fear of a "big bang" approach led to splitting the intended large system into two separate acquisitions, with the assumption that the two systems could later be integrated into a large SoS. But the second program suffered a very long and complex protest and did not get underway until several years after the first had begun. By that time, the first had completed most of its requirements and was nearing initial operational deployment. But there had been no input from the stakeholders of the second system about the interfaces that would be needed to make eventual integration of the two systems feasible. Thus, the plan for integrating the two systems was abandoned, and the second program was eventually cancelled. The first program fielded a system that provided only a small portion of the expected functionality.

In general, in the presence of this anti-pattern, one of two immediate consequences will emerge. Either the acquisition strategy is ignored as the program unfolds or the program is forced to bend the needs of the system to the inappropriate strategy. In the latter case, the system can reach a point where it can no longer meet its mission goals, business goals, or both.

Overlooking Quality Attributes

Context. In the earliest stages of a program's life, there may be no formal program office and only minimal accompanying funding to perform necessary work. Further, there is significant pressure to rapidly produce the acquisition strategy and initial architecture in order for the program to be funded. But there is no requirement to use quality attributes to define that architecture, and little incentive to do so. Further, in many cases, the detailed business goals are unwritten (see anti-pattern #1) or the importance of the software is ignored (see anti-pattern #5), and hence, there is little opportunity to expose the quality attributes that the system is expected to manifest.

Problem. The program overlooks the software quality attributes that should support the goals, whether mission or business. Instead, programs rely on key performance parameters (KPPs), which are not broken down in sufficient detail that architects can reason about the necessary alignment among the software architecture, system architecture, acquisition strategy, and aggregate set of goals for the system.

Observed Response. In order to meet the reporting needs and get to a "go" or "no go" decision for a system, programs put their engineering resources into eliciting and capturing the functional capabilities and requirements and provide only minimal attention to quality attributes by focusing on a limited set (e.g., performance, availability). Worse, the notions of those quality attributes are more often those understood by system engineers rather than software engineers.

As a result, architectural decisions that should be based on extensive consideration of all quality attributes—software as well as systems—are made by "gut feel," or by adopting an architecture from a similar or idealized system, rather than by reasoning that placed real importance on the specific software quality attributes for the system at hand.

Consequences. This anti-pattern was observed in four of the programs under study. In one joint program, the system was to be integrated into operations in each of the military Services. However, the concept of operations for each of the Services was different (i.e., where the system would be hosted, security needs, what other systems would be integrated), and these differences, all of which implied different quality attributes, were not recognized early in the program. Neither the acquisition strategy nor the architecture accommodated these differences. The quality attribute descriptions that were constructed reflected the needs of only one of the Services and focused only on technical issues; they explicitly ignored that same Service's business goals. It eventually became apparent that the program office and the end users had very different approaches to meeting even the single Service's stated needs.

In general, the primary consequence of this anti-pattern is that the resultant system architecture (and the likely inefficient software architecture) will satisfy only some of the goals; others will be, at best, partially satisfied and often unsatisfied. In the longer term, since sufficient knowledge of the quality attributes is lacking, the program will not have the strong analytic base needed to fully understand the impacts of different modes of evolution that might be needed over the system's life cycle.

Countering the Patterns

The anti-patterns described in the preceding section provide evidence of undesirable behaviors that are repeated across multiple programs. We believe that these undesirable behaviors are not intentional but indicate flaws in the existing approach to the acquisition of software-reliant systems. We also believe that at least part of the solution to this problem lies in analyzing how these anti-patterns operate at both the micro level and the macro level. In the previous section, we examined the individual consequences of each anti-pattern. In this section, we consider how, in combination, they jointly can affect the major entities that participate in the acquisition process.

Necessary Entities and Artifacts

The anti-patterns we observed relate to a small number of distinct entities, each of which has major importance for a program and the system it is building. For instance, one anti-pattern focused on how programs ignored the impact of quality attributes. There is ample evidence and experience, such as that discussed by Gagliardi, Wood, Morrow, and Klein (2010), showing that the main drivers for software architecture should be the quality attributes that the system must exhibit. These quality attributes are derived from another key entity, the mission needs expressed by stakeholders.

Another anti-pattern dealt with business goals that were either only expressed generally or only implicitly understood. The business goals for a program are an additional key entity. But these are likely the goals of a very different set of stakeholders. Although not commonly understood, the business goals, like the mission goals, will have quality attributes that should be the main drivers for the acquisition strategy; we assert that these other quality attributes are as important as those derived from the mission goals. We will refer to these other quality attributes as *acquisition quality attributes*.

Given these two sets of goals, which in turn are the principal drivers for two very critical entities (i.e., the acquisition strategy and the software and system architectures), the

potential for conflicts between those goals is large, as is shown in the anti-pattern of conflicting goals.

Finally, the notion of “the stakeholders” embodies a complex and diverse collection of individuals and organizations; they are the sources for the goals and the recipients of the benefits of the system to be created.

We posit several key entities of interest:

- mission goals
- the (mission) quality attributes implicit in those goals
- business goals
- the (acquisition) quality attributes implicit in those goals
- the acquisition strategy
- the software and system architectures, which are closely related, but separate
- the different sets of stakeholders who have expressed needs that are captured by the mission and business goals

While these entities represent a diverse set of things, including humans (stakeholders) and intangibles (goals), we posit that all of these entities must, at least in some manner, be manifest in physical artifacts. Some such artifacts are immediately obvious: the mission goals will ultimately be reflected in a requirements specification; an acquisition strategy document is mandatory for any program. Other artifacts are less well defined and may not even be present in a given program. We assert that they are just as necessary.

The stakeholders for a given acquisition, for instance, cannot be a vague collection of unknown persons but must be defined with at least minimal specificity: “the HR personnel who do data entry for the Air Force Logistics Command,” “the Assistant Secretary of the Navy for XYZ,” and so forth. The definition of the stakeholders may not have a formal document type associated with it, but it must be physical: There must be some way to determine who precisely has one or another goal, if only to assist in determining priorities and negotiating conflicts. Similarly, the business goals themselves may first be only general expressions found in a statement of need. But eventually those must find some form of detailed notation in a physical document that is a real analog to a requirements specification. Thus, we assert that each of the entities listed previously has an associated artifact, which we can inspect, reason about, and compare with other artifacts of the acquisition process.

Necessary Relationships

These entities are related to each other by means of several different relationships. For each, we use the formula “Entity X <relationship> Entity Y.” The following are the pertinent relationships identified in our analysis:

- <have>
- <are embodied by>
- <are consistent with>
- <drive>

- <constrains>
- <informs>

We show these entities and relationships in Figure 1. Some relationships are unidirectional, and the arrow indicates which entity is the actor (e.g., for “X <drive> Y,” the direction of the arrow is from X to Y). Some of these relationships are reflexive (e.g., “X <informs> Y” *and* “Y <informs> X”). In these cases, the arrow is two-headed.

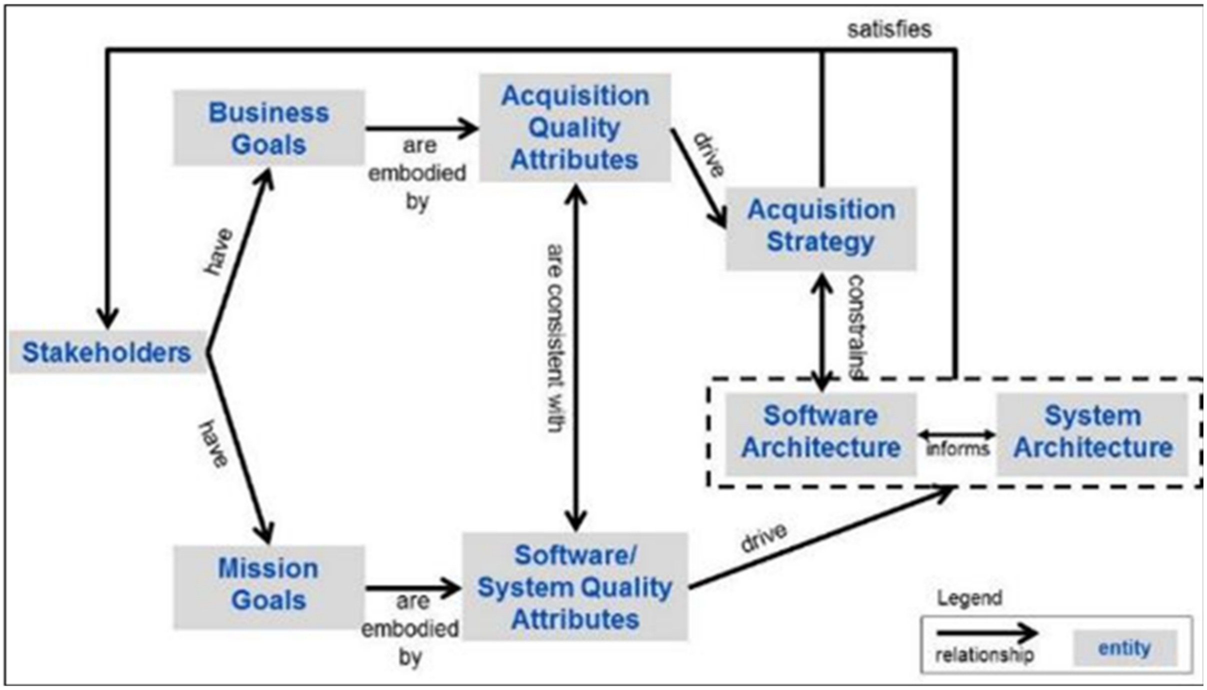

Figure 1. Key Entities and Relationships Identified During Our Analysis

When we consider these entities and relationships in light of the anti-patterns, we see the following:

The <have> relationships concern anti-patterns #1 and #4. While stakeholders have business goals, these goals are often not expressed; the problem is exacerbated by the lack of a process for recording business goals. If these goals can be captured so that the collection of business goals, stemming from all stakeholders, exists in a coherent document, then anti-pattern #1 cannot occur; the business goals will have been documented. If a program office captures and records these goals, then the office can reason about changes in the acquisition environment. It can determine whether the inevitable changes can be accommodated within the program’s current scope or whether a reset of the acquisition strategy or the architectures or both will be required. If a program office can perform such reasoning then, although turbulence in the acquisition environment cannot be prevented, the program office can have an appropriate response to the turbulence and prevent the occurrence of anti-pattern #4.

The <are embodied by> relationships concern anti-pattern #7. If the business and mission goals are analyzed and re-expressed in terms of acquisition quality attributes and software/system quality attributes, respectively, then anti-pattern #7 cannot occur since the quality attributes will have been carefully analyzed as part of program creation.

The <are consistent with> relationship concerns anti-pattern #2. Assuming that all of the relevant quality attributes (software, system, and acquisition) have been clearly expressed, it will be possible to reason about all quality attributes, comparing and performing tradeoffs between the types of attributes. If the quality attributes are consistent with each other, then conflicts among the goals will have been resolved and anti-pattern #2 will not occur.

The <drive> relationships concern anti-patterns #5 and #6. Years of research and practical usage of quality attributes have demonstrated that they should be the primary influences on both software and system architectures (Bass, Clements, & Kazman, 2012). In the situations where the quality attributes are used to create the architectures, then we can be certain that those qualities important to the program have been considered and the resultant architecture is consistent with the quality attributes. In such a case, anti-pattern #5 cannot occur. Similarly, if the acqusition strategy is derived from the quality attributes that have been developed from the business goals, then it is likely that the strategy will indeed reflect all of the stakeholder expectations and cannot be considered to be inappropriate to the institutional goals of the organizations involved, thus preventing the occurrence of anti-pattern #6.

The <constrains> relationship concerns anti-pattern #3. Even when the acquisition strategy and the software architecture are specifically aligned, this alignment must be maintained through the life of the system and/or the life of the program office. As the system matures, new goals emerge that must be accommodated in the acquisition strategy or the architecture or both. Ensuring that the architectures continue to constrain the acquisition strategy and the acquisition strategy continues to constrain the architectures will increase the likelihood that the program is feasible. In such a way, anti-pattern #3 can be prevented from occurring.

The <informs> relationship does not specifically concern an observed anti-pattern. Nonetheless, considerable research has shown the importance of mutual influence between software and system architecture. Maier (1998) succinctly described the different perspectives and the impact of not explicitly balancing the engineering and managing between these two architectures. We therefore include it here for completeness.

Figure 2 summarizes the anti-patterns as they affect the entities and relationships.

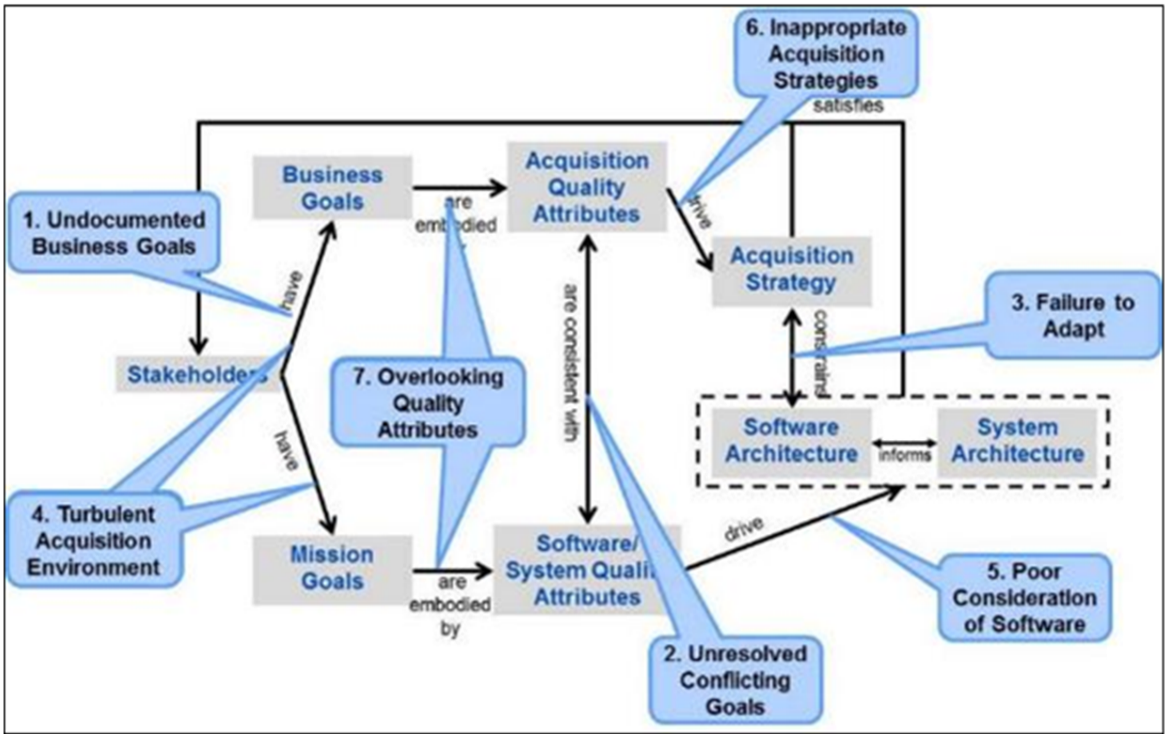

Figure 2. Anti-Patterns That Affect Specific Relationships and Entities

Acquisition Quality Attributes

A key aspect in our work is the notion of *acquisition* quality attributes. This represents a new concept and is the focus of our current investigations. We have introduced them because we are motivated by the considerable body of work on *software* quality attributes and expect that the acquisition quality attributes are as important to acquisition strategy as software quality attributes are to the software architecture. Because we see such a close analogy between these two types of quality attributes, we believe that research into these attributes can be modeled on the research into software quality attributes.

Role of Acquisition Quality Attributes

Acquisition quality attributes are derived from the business goals and exert their strongest influence on the acquisition strategy. They relate the business goals to the acquisition strategy in the same way that the software quality attributes relate the mission goals to the software architecture. To formulate acquisition quality attributes for a program implies the following step of explicitly developing an acquisition strategy that accommodates them: They must be designed into the strategy to minimize the risk of failure. Note that incorporating these qualities into the acquisition strategy is no guarantee that the program will be successful, but it lays the foundation upon which success can be built.

As with software quality attributes, acquisition quality attributes will be dependent on the specific circumstances of the program in question. For example, a program may have little concern for long-term sustainability if there is little expectation that the deployed system will be sustained over the long term; hence, the acquisition strategy should be concerned about many quality attributes but *not* about sustainability. (This can occur in situations where there is an imperative need to get something deployed as rapidly as possible.). Or a program may be developed as a research prototype with no concern about deployability or sustainability if the major goal is to prove a concept, not field a capability. The key point is

that these attributes must be understood in the context of each particular program so that a suitable acquisition strategy can be developed.

As with software quality attributes, we expect that some acquisition quality attributes will be universal. Thus, every program is started with some sense of producing a good result, and we would expect every program to have some sense of "achievability," although precisely what that means would differ from program to program. Similarly, programs with the goals for a long lifetime will exhibit sustainability and evolvability; if not, the programs are unlikely to enjoy their long life spans without major, costly adjustments over their lifetimes.

Giving Meaning to Acquisition Quality Attributes

As stated previously, our view of acquisition quality attributes is that they are an analog to software quality attributes, although the qualities they relate to may differ. And like software quality attributes, they have little inherent meaning that is not ambiguous and must be given precise meaning by some other mechanism.

One approach would be to try to develop precise definitions of each acquisition quality attribute. Our experience, however, is that this would lead to the same difficulties found with software or system quality attributes, where many different and inconsistent quality models exist and the definitions are either too general or too contradictory to be of use. (For instance, one could conjecture many definitions of *sustainability*, but which definition was appropriate to a specific program and system would still need to be resolved.)

Instead, we follow the approach used in software architecture (and later, system architecture) of developing scenarios, which have the purpose of defining precisely the meaning of the attributes in the context of a specific acquisition. Such an approach eliminates needless discussion about the "correct" definition of any individual attribute and, more importantly, gives meanings based on the context of a particular acquisition.

The software architecture work at the SEI was of great benefit in representing quality attribute scenarios in six parts: source, stimulus, artifact, environment, response, and response measure (Barbacci et al., 2003). Following this approach, we characterize the parts of an *acquisition* quality attribute in the same manner:

- *Source*: The person, group, or organization that generates the stimulus.
- *Stimulus*: A condition or event that needs to be considered when it occurs during the acquisition.
- *Environment*: The conditions under which the stimulus occurs.
- *Artifact*: The artifact that is stimulated.
- *Response*: The activity undertaken after the arrival of the stimulus.
- *Response measure*: When the response occurs, ideally this will be measurable in some fashion so that the scenario is testable.

As an example, in one program, an acquisition quality attribute scenario for "flexibility" could be described by this scenario: "In an environment where the continuing resolution bans new program starts, warfighters in the field demand new capability now. The new capability is added to an existing development contract without change in scope." The scenario elements would then correspond to

Source: Warfighters in the field

Stimulus: … demand a new capability now.

Environment: The continuing resolution bans new program starts

Artifact: … and so an existing development contract

Response: … is modified to add the desired capability

Response measure: … without change in scope

Yet in another program, the same quality attribute of “flexibility” could yield a somewhat different scenario due to the differences between the programs. For example, this other scenario might be: “In an environment where the deployment strategy has not yet been defined, warfighters in the field demand new capability now. The existing development contract is modified to provide an early delivery of the desired capability.” Here, the scenario elements are

Source: Warfighters in the field

Stimulus: … demand a new capability now

Environment: The deployment strategy has not yet been fully defined

Artifact: … so the development contract

Response: … is modified to provide the desired capability

Response measure: … to support an early delivery

In both of these cases, the scenarios provide specific meanings for “flexibility” but also indicate how they would imply different acquisition strategies for the two situations.

Working With Acquisition Quality Attribute Scenarios

We expect that the notion of acquisition quality attributes has the same relevance to the acquisition professional that software quality attributes have to the software architect. Thus, in practice, we would hope that a valuable exercise for an acquisition team early in a program’s life would be to consider the program they are defining in terms of the acquisition quality attributes implied by the program’s business goals (whether explicitly stated or otherwise). In such an exercise, we start with the business goals and, for each one, elicit one or more acquisition quality attributes. These are then used to elicit detailed scenarios that would give precise meaning to the quality attributes. One of the most effective mechanisms for eliciting scenarios is through guided brainstorming where appropriate stakeholders volunteer scenarios that are subsequently reviewed for their importance. One key issue is to explicitly consider the difficulty of satisfying the scenarios. Scenarios that are both of high importance and difficult to satisfy are the ones that will receive the most attention during the subsequent analysis.

Again, working as a group, the scenarios must then be analyzed for consistency with each other. If the consensus is that some scenarios are inconsistent with others, this implies that some business goals are inconsistent with each other and that the program cannot satisfy all of those goals. Ideally, conflicting business goals will be negotiated by the stakeholders until they no longer conflict, thus leading to an acquisition approach that can satisfy the stated goals.

Because acquisition quality scenarios define how the program must respond to events, the scenarios can now be used to determine whether a proposed acquisition strategy will allow the program to respond appropriately to expected future events. The collection of scenarios can be used to shape the program’s acquisition strategy so that it will embody the negotiated goals for the program.

Finally, we expect that both the elicitation and analysis of acquisition quality attributes, and their associated scenarios, can be combined with the elicitation and analysis of software quality attributes. In such a case, the consistency analysis can account for both software and acquisition quality attributes, thereby leading to a negotiation between mission and business goals. Although harmony between the two sets of scenarios does not guarantee program success, we posit that if there are conflicts between the software-based and acquisition-based scenarios, it is extremely likely that the architecture will conflict with the acquisition strategy and be a significant detractor to program success.

We are currently in the process of validating our assertion that acquisition quality attributes can be used to define the relationship between business goals and acquisition strategies. We are performing this validation by reviewing various programs, extracting their business goals, developing plausible scenarios, and then defining pieces of the acquisition strategy that would satisfy the scenario.

In addition, we are examining several cases of long-lived programs where we can clearly distinguish between the original goals for the program and changes to those goals. Through interviews, we extracted the business goals and the associated acquisition strategy that the programs adopted, developing acquisition quality attribute scenarios as examples. As new goals were added, we developed new acquisition quality attributes. Our goal with this exercise was not to second-guess or judge the original acquisition strategy but, rather, to show that scenarios can be found to be consistent or in conflict and that the new scenario can be used to judge the effectiveness of the existing acquisition strategy.

Conclusions and Next Steps

Alignment between the architecture and acquisition strategy does not occur naturally. Our research has revealed seven behavioral patterns, or anti-patterns, that lead to misalignments, which have contributed to program restarts, cancellations, and other failures.

We have also learned that the effect of these anti-patterns can most easily be observed through several key entities, and the relationships that should hold between and among them. A key insight derived from this research is that the relationship of the acquisition strategy to the business goals is analogous to the relationship between the software architecture and the mission goals. Our continuing investigations include developing acquisition quality attributes with associated six-part scenarios and validating that they can be used to distinguish between appropriate and inappropriate acquisition strategies.

Our future goal is to create an *alignment method* that assists program office personnel to systematically identify probable areas of mismatch between business and mission goals, acquisition strategy, and software architecture. With such a method, two outcomes would be feasible: (1) program managers can build acquisition strategies that more systematically eliminate one key cause of program failure, and (2) acquisition overseers can better evaluate the adequacy of the acquisition strategy as programs move to different life cycle phases. While this alone will not guarantee program success, we believe that it could be a significant factor in avoiding failures.

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Fewer Mistakes on the First Day: Architectural Strategies and Their Impacts on Acquisition Outcomes

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Abstract

Reducing cost and development time, while preserving acceptable levels of performance, is a priority for all government-sponsored complex product development. One avenue for improving outcomes is to use architecting strategies to guide development decisions. Frequent examples are commonality, interoperability, modularity, flexibility, extensibility, robustness, openness, and adaptability. A second avenue for improving outcomes is better acquisition strategies. The two are often considered in isolation. This paper begins an examination of how the choice of architecting strategy affects the choice of acquisition strategy, and vice versa.

As a first step, the paper synthesizes existing literature and provides straightforward definitions of each of the architecting strategies. As a second step, the paper maps each of the defined architecting strategies against two common axes of acquisition design, specifically openness to competition and sensitivity to requirements change. The conclusions, while tentative, show that increasing attention to the interaction between how systems are designed and how they are acquired may have a significant effect on the cost, schedule, and performance of complex product development.

Introduction

Reducing cost and development time, while preserving acceptable levels of performance, is a priority for complex product development in both military and civilian systems. One avenue for improving development is to use particular architecting strategies to guide high-level development decisions. These strategies reflect the priorities that the customer places on different aspects of the product. Different strategies lead to different design decisions and ultimately different outcomes. For example, developments based on the “robustness” strategy might trade high performance under specific conditions for acceptable performance over a range of conditions. This paper considers common, modular, open, flexible, adaptable, robust, extensible, and interoperable architecting

strategies. Many of these strategies have at one time or another been exhorted as the solution to acquiring complex products.[1]

However, there appears to be a disconnect between the use of these strategies and their effect on complex product development, particularly in the government sphere. New architecting strategies are encouraged at the highest levels, but the cost of acquiring new complex systems continues to climb (Berteau et al., 2010; Peters, 2009; Moore, 2011).

We observed two factors that we hypothesized to be likely contributors to the lack of impact of these architecting strategies on project acquisition costs. The first factor is a lack of effective communication about what the architecting strategies mean, caused by a scarcity of definitions for the strategies, and compounded by the application of the strategies in engineering disciplines far removed from where the terms were first used. The second factor is a universal application of the strategies to all acquisitions, rather than to just those acquisitions where the strategy would be particularly relevant and helpful.

The existing literature does not provide sufficient guidance on the architecting strategies, or the types of product acquisitions where they should be applied. The Defense Acquisition University (DAU) provides an excellent start, with brief definitions of many of the important terms in its *Glossary of Defense Acquisition Acronyms and Terms* (Hagan, 2009), although *flexibility*, *adaptability*, and *extensibility* are not defined. A symposium paper from the MIT Engineering Systems Division discussing architecting strategies generally is also useful, but does not specifically define the strategies and the differences between them (Crawley et al., 2004). The DoD dictionary, which consolidates definitions provided in doctrine documents, defines only commonality (Joint Chiefs of Staff, 2010). Finally, even within the top 100 articles found doing a Google Scholar search for articles containing the words *robust*, *flexible*, *common*, *interoperable*, and *extensible*, none sets out definitions for these terms. Although these searches may not be exhaustive, they represent a much more detailed search for definitions than a professional is typically able to conduct when investigating architectural options.

The specific objectives of this paper, therefore, are twofold. First, the paper aims to synthesize existing definitions of the design strategies into a single definition. This synthesis will provide a starting point for discussion of what the design strategies mean. Extensive comment and discussion about these definitions is anticipated, but consolidating all definitions into a single document and posing possible definitions for discussion is a prerequisite for this discussion, and represents an advance on the existing literature.

Second, the paper aims to provide a coarse analysis of the acquisition scenarios to which each strategy is well suited. Such an analysis makes the broad point that different acquisition scenarios merit different design strategies, and not one design strategy is a panacea for all acquisition challenges. The analysis also makes more specific findings about the regions of suitability of each design strategy, in terms of certainty of requirements and openness to competition.

In Section I, the paper examines the literature in detail. It presents a number of observations about the potential for confusion in the existing literature, and also highlights

[1] *Commonality*: "Commonality is the key to affordability" (DoD, 2013). *Interoperability*: "It is DOD Policy that . . . Department of Defense pursue materiel interoperability with allies and coalition partners" (Carter, 2009). *Open Systems Architectures*: "[Acquisition Professionals within DOD will ...] require open systems architectures" (Carter, 2010). "Program managers shall employ MOSA [Modular Open Systems Approach] to design for affordable change, enable evolutionary acquisition, and rapidly field affordable systems that are interoperable in the joint battle space" (DoD, 2008).

how reference is frequently made to the design strategies without an accompanying explanation of what is meant by those strategies. In Section II, standard definitions for each of the chosen architecting strategies (common, modular, open, flexible, adaptable, robust, extensible, and interoperable, referred to as the "Eight Strategies") are proposed. Each definition is illustrated with examples from previous government acquisitions. Section III presents an analysis of the newly defined design strategies against two important acquisition parameters: (1) certainty of requirements, and (2) number of organizations involved.

Finally, Section IV concludes the paper and presents suggestions for further work in this area.

The Existing Literature Confuses More Than It Clarifies

If architectural strategies are to be used for complex government acquisition projects, there is a need for all involved to understand the meaning of these strategies. This section of the paper reviews the existing definitions of architectural strategies and considers whether the definitions are consistent and easy to find. Definitions that are consistent and easy to find would be expected as a prerequisite to effectively using the architectural design strategies across government acquisitions.

At the outset, it is important to be precise with terminology used in this paper. An architecture is "an abstract description of the entities of a system and the relationships between those entities" (Crawley et al., 2004). Put another way, architecture is "the arrangement of the functional elements into physical blocks" (Ulrich & Eppinger, 2008). Architecture is the underlying concept of how a complex system is brought together, the process of relating form to function in order to create value where value is benefit at cost.

Different architectures have different properties. When the architecture clearly brings about a certain property in the final system, the final system is often referred to as having a "property-architecture." For example, if the architecture is such that the final system is robust, then the system is described as having a robust architecture. We refer to the process of designing an architecture for a desired result as an architecting strategy.

Surprisingly, we were able to find only a small number of references that presented and compared all or most of the architecting strategies. De Weck, Ross, and Rhodes (2012) investigated most of the architecting strategies presented in this paper but were concerned with them as "system properties" rather than architecting strategies. Their paper also focused on the interrelationships between the strategies rather than describing the strategies themselves. The symposium paper by the MIT Engineering Systems Division, *The Influence of Architecture in Engineering Systems* (Crawley et al., 2004), investigated definition in more detail. The paper described how architecture influences the properties of created systems, resulting in robustness, adaptability, flexibility, safety, and scalability. However, Crawley et al. focused on the importance of architecture rather than detailing different outcomes from the architecting process. Fricke and Schultz (2005) presented an excellent side-by-side view of adaptability, agility, flexibility, and robustness, but they did not extend their analysis beyond these "changeable" architectures.

Finding other papers that compared architecting approaches proved difficult. A Google Scholar search for articles containing the words *robust*, *flexible*, *common*, *interoperable*, and *extensible* gives a surprising number of results—13,800—but no paper in the top 100 sets out definitions for these terms. In other cases, papers defined a few of the terms in domain-specific areas. For example, Ferguson, Siddiqi, Lewis, and de Weck (2007) examined flexible and reconfigurable systems in product design, but their definitions would

require thought and interpretation before application to another area, for example, information architectures.

Nor is there assistance from the key textbooks in the area. The Art of System Architecting mentions some of these architecting strategies but does not contrast them or provide extensive detail. In *Architecture and Principles of System Engineering*, Dickerson and Mavris (2010) did not present definitions for any of the Eight Strategies. However, the terms themselves are mentioned, in some cases, in the sense we use them ("interoperable and cost effective military systems" [Dickerson & Mavris, 2010, p. 148], "methods and techniques to … design for robustness relative to uncertain operational environments" [p. 313]), and in other cases in very different contexts (for example, *openness* is used in the context of stakeholder discussions, and *flexibility* in the context of "development flexibility, such as environmental limitations or regulatory standards").

In the government context, the situation does not improve greatly. A complete set of definitions does not exist. Of the Eight Strategies, the DoD dictionary, which consolidates definitions provided in doctrine documents, defines only commonality (Joint Chiefs of Staff, 2010). The DAU provides brief definitions of many of the important terms in its *Glossary of Defense Acquisition Acronyms and Terms*, although flexibility, adaptability, and extensibility are not defined (Hagan, 2009). Further, some of the terms are narrowly defined. For example, *module* is used only in the context of software architectures. The DAU's online "Terms and Definitions" (2013) defines three out of the Eight Strategies, and defines the substance of extensibility, though referring to it as scalability.

Compounding the problem, the same term is used in the same community to mean different things. Defense Directive 5000.01 (Wolfowitz, 2007) emphasizes five key acquisition policies, one of which is flexibility. Dickerson and Mavris (2010) summarized flexibility in this context as the "need to structure each acquisition program according to the set of strategies, documentation, reviews, and phases that make sense for this program" (p. 290). This is a different definition of flexibility than used by system architects in describing the properties of their systems. However, there are some bright spots in the government landscape. The push towards a "modular, open-systems architecture" by the Open Systems Joint Task Force (2004), shows significant development of the modular and open systems concepts through tens of pages of principles, definitions, and examples.

Definitional confusion is not entirely due to a deficiency in the literature, however. The architecting strategies are often mentioned in the same breath but in fact are concerned with quite dissimilar things. *Adaptability*, *flexibility*, and *robustness* are characteristics of an end-product that describes how the product interacts with its environment, especially as that environment changes. *Extensibility* describes how the product is able to improve over time. *Interoperable* describes how the product interacts with other products in the operations phase. *Commonality* describes similarities with other products, usually in the development and operations phases. *Modularity* describes the physical structure of the product. *Openness* describes the process of acquiring the product. Therefore, it is not surprising that a single paper does not cover the range of architecting strategies, because they are quite different.

Further, the architectural strategies inter-relate. Modularity emphasizes simple, well-understood interfaces and so enables commonality (through reuse of existing products) and openness (by more easily tying together the contributions of different participants). Interoperable architectures require knowledge of the systems that interoperate, implying some level of openness. Interoperable architectures also work because of some degree of commonality, usually in the patterns of information exchange, so an interoperable

architecture could also be described as having, for example, a common communications protocol.

The difficulties with using the existing literature to define architecting strategies can therefore be summarized as follows:

- No single reference presents and compares all the architecting strategies.
- Several key references refer to architecting strategies without defining them, assuming that they are well understood.
- Where definitions are provided, they are often domain-specific.
- The words chosen for the architecting strategies are sometimes used by the same communities, with different meanings.
- The strategies interrelate, and multiple architecting strategies are often used to achieve a given result.

Although this may appear a formidable list of obstacles, clear, widely available definitions of the architecting strategies will assist with resolving all of these difficulties. In the defense acquisition context, referring to the definitions of these strategies when proposing them as mandatory considerations in acquisition would improve communication of the desired outcomes. There is a precedent for such definitional foundation in the commonality literature. The RAND Corporation produced a report containing a standard commonality lexicon (Held, Lewis, & Newsome, 2007). A similar report examining the definitions described in Section II, with more detail and rigor, presents a possible solution to the current confusion in the literature.

Defining Architectural Strategies

In an attempt to remedy some of the confusion outlined in the previous section, this section provides an overview of architecting strategy definitions from the engineering literature, a relevant DoD example of each definition, a discussion of the definition as it relates to process versus architecture, and, because these strategies are often painted as a panacea for all new-product development ills, a description of the possible downsides of the approach. In the definitions that follow, we begin by discussing a simple example of each architecture strategy. Because low complexity examples are rare in the real world, we also discuss the application of each strategy to a more complex, and where possible, “system of systems” example.

Flexible Architectures

A flexible architecture is one that is easily modified to respond to changing requirements (Crawleyet al., 2004; Fricke & Schultz, 2005; Ferguson et al., 2007). The modification requires work to be done on the system. For example, an architecture that allows different external stores (often referred to as pods) to be loaded on military aircraft to provide different functionality for different missions would be described as a flexible architecture. External stores can provide numerous functions, including—but not limited to—weapons, additional fuel, electronic counter measures (ECMs), communications, and sensors. A more complex example is the ability to load different software onto pre-defined hardware, such as is expected from software programmable radios. Loading new software changes the functionality of the radio to suit the operating environment. In each case, the designers considered that easily changing the system performance was important, and allowance for such changes was built into the architecture. The architectural choices permit product flexibility and therefore are described as a flexible architecture. The benefit of a flexible architecture is that a particular design continues to perform even as the environment

changes. For example, an entirely new airplane is not required simply because the range requirements for a certain mission exceed the internal fuel storage capacity of the aircraft.

Flexibility is often associated with modularity if the flexibility arises through the swapping of modular parts (for example, weapons).[2] Flexibility need not be dependent on a modular architecture, however. A flexible system could allow for software changes to be inserted without even unpacking the part from the case, as in the case of the Block III High Speed Anti-Radiation Missile (HARM), a system designed to destroy radar equipped air defenses. The Block II HARM has its own software operating system, which can be upgraded in the field—and in the crate—to redefine its flight profile, its function, and how it interacts with the targeting system onboard the aircraft system.

Flexibility is not always a positive attribute, however, as there is a price associated with designing systems to be flexible. Flexibility should be used only where uncertainty of requirements for the system means that the strategy is required. Crawley et al. (2004) put this succinctly:

> In some cases, flexibility comes at a price—namely, efficiency in some form. Flexibility may require over-design, generic components, extra interfaces, or changeover time. A less flexible system might have more focused components, fewer interfaces, and no loss due to changeover.

Flexibility can in fact increase overall lifetime costs of a system, especially if the product lifetime is shorter than expected, due to the significant up-front cost. As the Army's Future Combat System program office pointed out in its reaction to a GAO (2009) report,

> Because of the significant amount of new technology development and the emphasis on laying a good, flexible architecture foundation, development effort/costs may not follow typical expenditure rates as other projects, and a larger percentage will be needed in the early stages of the program.

Adaptable Architectures

Fricke and Schultz (2005) described adaptable systems as systems that "deliver their intended functionality under varying operating conditions through changing themselves." In other words, an adaptable architecture modifies itself to meet a changing environment. An example from the commercial world is commercial power generation, which automatically brings additional power production online during high demand periods. In the defense context, an example of an adaptable system is radar. Most radar systems are able to change their receiver gain automatically in order to filter out noise generated by jamming.

The difference between flexible and adaptable is subtle, and in the experience of the authors, those using the terms do not always grasp the difference. In particular, either term is often used as a catch all for the meaning of both terms. The difference between adaptable and flexible architectures has important cost implications for DoD projects. Adaptability usually places significantly greater demands on a system than flexibility but may be warranted in some cases, for example, where human intervention is impossible[3] (such as a pacemaker), or where human reaction times are too slow (for example, the ACESII ejection seat, which automatically changes its ejection profile based on the altitude and airspeed of the aircraft at the time of ejection).

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[2] De Weck, Ross, and Rhodes (2012) showed this as a strong link in their diagram of "ility co-occurrence in the literature."

[3] In the DoD context, adaptability in the context of situations where human intervention is impossible is tied to autonomy, which is commonly not acceptable given the high stakes involved in warfare and the unwillingness to take the human decision-maker out of the loop.

There is also overlap with other terminology. An open architecting process could be described as a flexible architecture because it allows new design implementations to be introduced over time. An "extensible" architecture can also be changed over time and therefore be characterized as "flexible," albeit at the most inflexible end of flexible.[4] Finally, a modular approach enables flexibility but is not enough in itself to guarantee flexibility.[5] To conceptualize this, imagine a modular system, such as the aircraft with weapons discussed previously, where the weapons racks were welded to the aircraft frame. The design is no less modular, but the architecture is no longer flexible.

Robust Architectures

A robust architecture is one that is able to meet its performance specification over a wide range of, often unanticipated, external conditions and still perform well (Hagan, 2009; Crawley et al., 2004; Fricke & Schultz, 2005). This design strategy is often used when there is high uncertainty over the future performance requirements of a product (Thomke, 1997), or when the system itself is complex and not well understood (Crawley et al., 2004). The design approaches to achieve robustness are not well understood (Crawley et al., 2004), particularly in the area of software design. The benefit of a robust architecture is that the product keeps performing even as the external environment changes. Robustness may be preferred to flexibility or adaptability for a number of reasons. Robustness may be a lower cost approach because the system never needs to change. Robustness may also be preferred for situations where the range of environmental challenges is not well known. An example of a robust architecture from the defense context is the design of the Link-16 protocol, which assumed that message traffic might get lost in the dynamic airborne environment. Therefore, it built significant redundancy into its message traffic, sending positional data and other messages multiple times per second to ensure delivery. A classic example of a robust architecture is the nuclear command and control architecture. Built into mountains and underground silos, and designed to operate in a post-nuclear attack radiation environment, robustness was clearly a main design criteria.

System designs described as "robust" are more widely used than the strict definition above would allow. Some consider a robust design to be anything that copes with environmental changes and continues to perform. Robustness is also used as a synonym for survivability, to indicate continued performance when components of the system are damaged. Finally, some members of the defense community (perhaps showing some pessimism with the acquisitions process) use a robust design to mean one that actually works as designed under field conditions, using it interchangeably with "ruggedized" (Hawkes, 2013; Sherborne Sensors, 2013). To add to the confusion, Thomke's (1997) paper, which contains excellent case studies into what we would call "robustness" in the design stage, describes the cases as "design flexibility."

It is obvious that a robust architecture will usually be more expensive upfront than a conventional architecture. The greater span of requirements often necessitates more time preparing better designs or more cost in manufacturing, as more exotic materials are used. Therefore, as with any architectural design choice, there is a cost-benefit tradeoff for a robust design.

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[4] For clarity, systems that are intended to be changed back and forth many times are usually referred to as "flexible and reconfigurable" (Ferguson et al., 2007).

[5] A simple illustration of the link between flexibility and modularity can be seen with a Google Scholar search for ("flexible and modular" or "modular and flexible"), which yields ten times more results than ("flexible and robust" or "robust and flexible").

Open Architectures

Open architectures are becoming increasingly popular due to their prevalence, and success, in the software industry. Silver (2010) examined the history of open architectures in detail. An open architecture is one where the necessary information to design a part of the system is made accessible to the public or a wide group of possible designers. Hagan (2009) goes into more detail, defining an open system as

> a system that implements specifications maintained by an open, public consensus process for interfaces, services, and support formats, to enable properly engineered components to be utilized across a wide range of systems with minimal change, to interoperate with other components on local and remote systems, and to interact with users in a manner that facilitates portability.

The essence of these definitions is that open architectures allow any interested organizations to participate in the design and development of parts of the system. This is not a new idea, but the fact that individuals anywhere, equipped with only a computer, can contribute to open software development, combined with the increased importance of software to complex projects, has meant that the pool of potential contributors to open architectures has widened over recent decades. The benefit of an open architecture is that better solutions can sometimes be found because more organizations have the chance to examine the problem and propose design solutions. The increased competition also has the potential to lower costs.

An example from the defense context, though not yet officially sanctioned, is the growth of "Tactical iPhone apps" that have been developed both by soldiers and by small companies (Tactical Nav, 2013). These are built using the open interface exposed to applications developers by Apple.

Openness is generally well understood and difficult to confuse with any of the other terms presented here. It is important to recognize that openness is more concerned with the process of development than the attributes of the end-state of the product. However, the system architect is concerned with process as well as end-state because the development process affects affordability by changing development cost. Therefore, in developing and comparing architectural strategies, it is valid to consider strategies that affect process.

Open architectures have some significant drawbacks that are sometimes overlooked in the current enthusiasm for their use. Open architectures present coordination challenges for the government customer who must ensure that the products developed on the open market can interface to produce a usable end product. The broad dissemination of information about the end product may also present security concerns.

Common Architectures

A common architecture focuses on reuse of proven systems, or the design of platforms for later reuse (Wicht, 2011). With relatively simple systems, the key benefit is cost reduction, as much of the work from the first system is reused. Reusing systems and/or system components also decreases the development time associated with the system. With more complex systems, other benefits also become obvious: reliability increases because proven designs are reused and each part is used more often; maintenance and logistics are more affordable because there are fewer unique parts; less training is required as operators are familiar with previous instances of the product.

Examples from a DoD perspective include the Joint Strike Fighter (JSF), which was designed in three variants with as many common parts as possible.[6] Another example is the M61A1 20 mm cannon. This automatic weapon, often called the Vulcan, has been used in numerous Air Force aircraft (F-104, F-105, F-106, F-4, F-14, F-15, F-16, F-18, A-7, F-111D, and most recently the F-22), the Navy PHALANX system, and the Army C-RAM.

Commonality is straightforward in principle; however, it has significant overlap with modularity and interoperability. In a modular system, multiple common modules are often used to incrementally increase performance. The resulting system has strategies of both modularity and commonality. For example, some launch vehicles have a modular configuration with respect to the number of solid rocket boosters clustered around the vehicle core. For example, the Atlas V launch vehicle can have from zero to five solid rocket boosters attached to the core, depending on the particular payload and orbit of a launch.[7]

Modularity also makes reuse easier and therefore enables commonality at a lower cost. Software modules are the canonical example of this, because good practice software writing encapsulates particular software tasks into modules, with defined inputs and outputs. If that functionality is required in a subsequent development, the module can be easily transplanted into the new context. Commonality and interoperability are also blurred. Interoperability generally requires a common (or “standardized”) interface. Therefore, the two systems are interoperable, or they share a common interface. The outcome is the same, but the terminology could be used differently. We suggest that if commonality is used solely for standardizing communications protocols for interoperability, the guiding strategy is interoperability. However, if the rationale is life-cycle cost savings from common design of terminals, hardware, or training procedures, then “commonality” is probably more appropriate.

Commonality does not always produce benefits. For example, if requirements change and a new system is required, the additional up-front investment in designing a common system is lost. In some instances, the cost of designing and enforcing a common system outweighs the life-cycle cost savings of having the common system. This may be the case with the F-35, which has had “continuing manufacturing inefficiencies, parts problems, and technical changes [that] indicate that the aircraft’s design and production processes may lack the maturity needed to efficiently produce aircraft at planned rates” (GAO, 2011). The program was restructured in 2011, triggering a Nunn-McCurdy unit-cost breach. Performance is often penalized with a common system, with both systems having to share a system that suits neither of them perfectly.

Modular Architectures

To deal with complexity in systems, the idea of modularity is as old as engineering itself. Modularity allows a complex problem to be tackled in pieces. At its most basic, a modular architecture focuses on dividing the form of the system to reflect the functions of the system. This means that the system can be divided into chunks, each of which performs a distinct function. Baldwin and Clark (1999) had an elegant definition: “A module is a unit whose structural elements are powerfully connected among themselves and weakly connected to elements in other units.” This design strategy tends to produce “tidier” designs

[6] “The JSF program goals are to develop and field a family of stealthy strike fighter aircraft for the Navy, Air Force, Marine Corps, and U.S. allies, with maximum commonality to minimize costs” (GAO, 2009).
[7] United Launch Alliance described the Atlas V under the heading “Modular System for Maximum Flexibility and Reliability” as using “a standard common core booster™ (CCB), up to five strap-on solid rocket boosters (SRB)” (United Launch Alliance, 2012).

with associated benefits to reliability and re-work cost. Modularity standardizes interfaces and minimizes the amount of information that needs to travel across those interfaces. More advanced modularity defines standard interfaces between aspects of the form of the system, and allows those pieces of form to be swapped out to produce different functions. This allows the product to perform across a greater range of external environments and to be upgraded more quickly and cheaply. For example, the computer and USB-peripheral architecture now used on personal computers is a modular architecture. The defined interface is the USB, and different forms with different functions can be connected to the computer via USB to improve the function of the system as a whole. A defense example of modularity is the guided bomb unit (GBU). GBUs are basically a series of modular parts, including guidance systems, ordnance, and fuses, among others, that can be assembled from the modules based on the need. Depending on the target and the desired effect, weaponeers basically build munitions from standard modular parts. There are a number of different approaches to modularity (Crawley et al., 2004), but all revolve around the same idea of neatly encapsulating product functions inside aspects of form.

Discussions about modularity usually imply that modularity is beneficial for product development; however, this is not always the case. Modularity is beneficial if it assists the product in meeting its cost and performance goals, for example through enabling commonality, flexibility, or simply neater design with less re-work. Modularity requirements can be detrimental in applications where performance, space, or weight is at a premium. In these cases, modularizing the system may introduce unacceptable performance penalties. For example, an iPhone is a tightly integrated system. The touchscreen and camera are built into the casing, and the batteries are such an integral part of the unit that they cannot be separately replaced. This allows the iPhone to be made smaller, but makes it more difficult to reuse sections of the phone from model to model. Changes to the internal design between the iPhone 4 and the iPhone 4S meant that the positions of buttons on the case needed to shift.

This tight interaction, where changes to one part of the product necessitate other changes, is typical of tightly integrated systems.[8] A second example is writing high-performance software. The use of “libraries” (pre-existing code, the software equivalent of modules) is minimized, and their functionality often re-written completely in order to optimize it for a particular application. Only the code absolutely required for the program to run is included.[9]

Modularity also shows significant interaction with other architecting strategies, particularly open architectures. This is because openness usually outsources many of the design tasks, reducing the ongoing communication between the system architects and the product design teams, and increasing the risk of integration difficulties. Modularity’s emphasis on clearly defined interfaces and each module performing a single function mitigates integration risk, and therefore works well with an open architecture. An example of modularity and openness working together is the development of apps for smartphones. The apps are modular add-ons to improve the functionality of the phone and can be developed by anyone (i.e., a partially open architecture). In the defense context, modularity has been combined with open systems, which modularity enables. The result is “modular open-systems architectures.” DoD Directive 5000.1 states that “acquisition programs shall be managed through the application of a systems engineering approach that optimizes total

[8] See, for example, Giffin et al. (2009), who found less change propagation through a system where “the architecture of [the] system was carefully crafted to be modular from the start.”
[9] “In structured software design, functionality and data is arranged in software modules” (Chakrabati, de Alfaro, Henzinger, Jurdzinski, & Mang, 2002).

system performance and minimizes total ownership costs. A modular, open systems approach shall be employed, where feasible” (Wolfowitz, 2007). This is another example of constructive interaction between two architecting strategies.

Interoperable Architectures

Almost all systems are interoperable with some other systems because nothing works in absolute isolation. Most electronic devices are interoperable with mains power; most computers are interoperable with Internet servers; most vehicles are interoperable with the highway systems in the countries for which they were built. Exceptions to these rules exist, but only in specialized applications. When we use the word *interoperable architecture*, therefore, it is not to describe these common situations where the interoperability is implicit, but rather to describe systems where the interoperability is a key requirement of the user.

Further, interoperability is what defines systems in the sense that if there is no interaction, there is no system. If a broader perspective is taken, any product that is interoperable with another can therefore be seen as simply two parts of a single system. For example, one type of radio mounted in a ship could be described as interoperable with another type of radio mounted in an aircraft. Or, a broader system could be considered that includes both radios, in which case the interoperability is internal to the system. Therefore, simply depending on where the boundaries of the system are drawn, an interoperable architecture can refer to interoperability with systems outside the architecture or interoperability with systems internal to the architecture.

The first view of “interoperable” is used to describe architectures capable of interfacing with specified systems external to the architecture under consideration, in order to improve its functionality. This is the usual level of consideration of the architecture and is the substance of Hagan’s (2009) definition of interoperability:

> The ability of systems, units, or forces to provide data, information, materiel, and services to and accept the same from other systems, units, or forces and to use the data, information, materiel, and services so exchanged to enable them to operate effectively together.

Making a system interoperable usually increases the usefulness of that architecture. For example, designing a radio handset that can use existing waveforms increases the number of other radios with which it can communicate. The ability to interoperate external to the architecture under consideration permits wider communication than developing a new, unique waveform. This would usually make a more useful product than developing a new radio in isolation.

The second way is a high-level view in which the elements of the architecture under consideration are themselves interoperable. This second view was referred to as “intra-operability” by the Open Systems Joint Task Force (2004). For example, in designing a military communications network like the Joint Tactical Radio System (JTRS), a guiding principle was that any radio on any platform running the same waveform could communicate. The JTRS architecture could therefore be described as an interoperable architecture, with the interoperation occurring within the system. To be more specific, this high-level view is often used for systems with separate physical elements that communicate information and where interoperation is not essential to the design. It would not be common to say that a set of radios designed for use by groups of infantry was an “interoperable architecture” because radios that are not interoperable with each other are generally useless. However, in the case of the JTRS, where radios on aircraft could interface with radios on ships and in the hands of infantry, this was an unprecedented degree of

interoperation that was central to the JTRS project. Therefore, describing the JTRS as an "interoperable architecture" adds information about the central design strategy.

Interoperable architectures also present some disadvantages. The increased cost and complexity of design involved in making an architecture interoperable should not be overlooked. In particular, interoperable architectures are difficult to test because the boundaries of the system under test are often unclear or difficult to simulate in real-world conditions.

A common issue with implementing interoperability is different implementation of the standard. An example is the Link-16 standard message set, which has been implemented differently across various systems, resulting in suboptimal interoperability.

Extensible Architectures

An extensible architecture is one that makes provision for additional elements to be added in the future. In contrast to a flexible architecture, where the guiding strategy involves addition and removal as needed, an extensible architecture generally contemplates permanent additions.[10] A striking example of extensibility is the practice of constructing future on-off ramps at the time of construction of highway overpasses. These "ramps to nowhere," which extend only a short distance out from the main bridge, minimize the cost and disruption of traffic if another road needs to be connected to the overpass at a future time.

In a DoD context, an example of an extensible architecture is the F-15E Strike Eagle, which, when it was built, was built and architected to support four radios but was initially fitted only with two. However, the space, the physical interface, and the interface with the Operational Flight Program (the software) were all developed and built in at the start. One of the two remaining slots has been subsequently filled. The disadvantages to the extensible architecture are primarily the additional up-front expense and time of building in the extensibility. The extensibility offers an easy target for scope reduction under cost or schedule pressure. Extensibility can also be difficult to test in complex systems because the elements to be extended are often not created; therefore, testing the interface under realistic conditions is difficult. When the government, not the contractor, is the ultimate beneficiary of the cost savings of a well-engineered extensible solution, there is little incentive apart from compliance testing to ensure that the extensibility is done well.

Extensibility has a relatively clear definition. It can be distinguished from flexibility through the permanence of the extensible addition. It can be distinguished from interoperability because at the time the extensible system is created, the system it will interoperate with is not yet created. Note that extensibility is very similar to scalability, and the two are often interchanged. Two criteria to distinguish the terms are proposed here based on our reading of the nuance in usage between the two, but these are by no means hard rules. First, *extensibility* usually refers to a bounded addition, where *scalability* usually refers to arbitrarily large increases in quantity. For example, extensibility could be used in the context of adding a second story to a building or an additional lane to a freeway. Scalability is more commonly used in information systems when unbounded increases in quantity are more feasible. For example, in a computer network architecture, a scalable system indicates the ability to add on more nodes arbitrarily. Secondly, scalability also

[10] No satisfying formal definitions of *extensibility* could be found in the literature, presumably because the term was widely used and understood. Wikipedia states, without citation in its entry on extensibility, that "in systems architecture, extensibility means the system is designed to include hooks and mechanisms for expanding/enhancing the system with anticipated capabilities without having to make major changes to the system infrastructure."

connotes additions that are similar or common to what already exists, where extensibility could include provision for something different. For example, an architecture that envisaged adding a garage to the side of a house might easily be described as extensible but less comfortably as scalable. The ability to duplicate an existing garage would be easier to describe as scalable but could probably also be described as extensible.

Summary of Engineering Literature Definitions

The definitions suggested previously are summarized in Table 1, highlighting the engineering focus of the design strategy, as well as some of the confusing overlaps of the terminology used to describe the end result. Note that the end goal is always to deliver the desired performance at required costs, and the architectural strategies should be considered as a range of tools to achieve that end.

Table 1. Architectural Strategies

Architectural Strategy	Main Focus	Major Benefits	Major Drawbacks
Common	Parts, rather than interfaces	Increased life-cycle affordability Manufacturability Reliability	Higher upfront costs Sub-optimal performance
Modular	Interfaces (designed, minimized, and standardized) One-to-one mapping of function to form	Leads to scalability Leads to flexibility Leads to commonality	Sub-optimal performance Added weight (in some cases)
Adaptable	Changes itself based on variations in the environment	More affordable than developing different products May improve survivability, reliability, or other performance characteristics	Requires well-defined requirements May require over-design, generic components, extra interfaces
Flexible	Gets changed by people in reaction to changes in environment	More affordable than developing different products May improve survivability, reliability, or other performance characteristics	Requires well-defined requirements May require over-design, generic components, extra interfaces
Robust	Continues to deliver performance despite substantial variations in environment	More affordable than developing different products May improve survivability, reliability, or other performance characteristics	Usually more expensive Lower performance
Interoperable	Standardizes interfaces	Improves performance May improve affordability through reuse of existing network infrastructure	Effort to correctly interface with existing systems Perpetuation of legacy standards
Open	Necessary design information made public	Encourages innovation that may improve affordability or performance Encourages competition, which may improve affordability or performance	Loss of design control, intellectual property, and project influence by customer
Extensible	Provisions made for future permanent additions	Improves affordability, assuming the extension is used	Higher upfront costs Difficult to test in development

Selecting and Aligning Architectural Strategies With Acquisition Goals

Equipped with a better understanding of the architectural strategies, we return to the challenge of how the acquisition community can make sense out of these terms and best apply an acquisition strategy to achieve the desired end state. The premise of this section is that some acquisitions are better suited to some architectural strategies.

Against the backdrop of several acquisition reform efforts, including the Weapon Systems Reform Act of 2009, the 2008 reissuance of DoD Instruction 5000.02 and the Under Secretary of Defense for Acquisition, Technology, and Logistics (USD[AT&L]) "Better Buying Power" memorandum (Carter, 2010), understanding the interrelation between acquisition strategies and architecting strategies becomes increasingly critical. These reforms place an increased emphasis on the systems engineering phase, as well as focus on cost performance throughout a program's life cycle (GAO, 2012). The Weapon Systems Reform Act of 2009, in particular, places an emphasis on competition throughout the program life cycle (GAO, 2012). The result of these efforts is that more time and money is being spent prior to system development or production, and more emphasis is being placed on competition at all phases, to reduce cost.

Each acquisition is unique. In attempting to give broad guidance to the acquisition community, this paper focuses on two variables that change how acquisitions are conducted and which architectural strategies may be most appropriate:[11] First, the degree to which requirements and environment change from the initial planning to the field-conditions of the system; and second, the number of contractors separately involved in delivering the end system. We consider a contractor separately involved in the acquisition if it is directly responsible to the government customer, rather than acting as a subcontractor. Multiple contractors may be introduced because the system under consideration is too large (in terms of cost or complexity) to give to a single company or to increase competition in the procurement process. Deputy Secretary Carter (2010) has already made the point that he wants increased involvement by a larger number of firms under the theory that it lowers costs, increases buying flexibility, increases the strength of the industrial base, and leads to company-driven innovation (in support of competition). The Weapon Systems Reform Act of 2009 requires the use of competitive prototypes prior to systems development to be a part of the acquisition strategy (GAO, 2012).

These two variables lead us to ask the following two questions for each of the Eight Strategies:

1. If this architectural strategy is used, how flexible can the procurement be to changes in the anticipated operating environment and/or requirements?
2. If this architectural strategy is used, how difficult is it to involve multiple, separate companies?

The results of asking these questions are presented in Figure 1.

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[11] Of course, other variables may also affect the choice of the architecting strategy, for example, the remuneration structure of a contract (choosing from fixed-fee, cost-plus, and incentive-fee, among others). The two variables we chose are not as well controlled by government than many other factors that affect acquisitions; therefore, the architectural approach needs to be tailored to the acquisition variables, rather than the acquisition variables being tailored to the architectural approach. For detailed examples on how acquisition variables could be tailored, assuming a commonality approach was taken (Wicht, 2011).

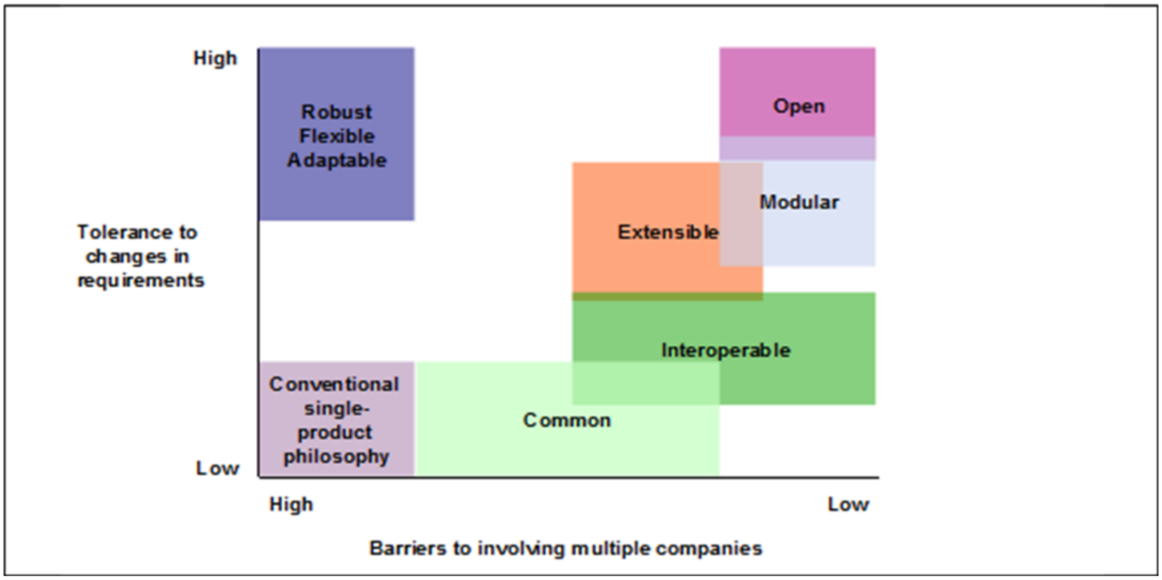

Figure 1. Architecting Strategies in Context

Figure 1 shows that, depending on where across the spectrum a given procurement falls, there are generally multiple architecture options that will achieve a good result, but there are also architectural approaches that are not well suited. The proposed framework described previously is offered as a starting point for identifying potential architecting strategies based on where on the spectrum a given acquisition is likely to fall. The architecting strategy is directly tied to cost-benefit trades for the product, and as a smart buyer and/or as a systems architect, the government must be aware of these architectural considerations. A detailed rationale for the position of each entry on the chart in Figure 1 follows.

Conventional, Single-Product Design Strategy. Conventional, single-product design strategy describes a conventional single product, single contractor development process where the government specifies the requirements up front and a single contractor produces the product. It has low tolerance to changes in the initial requirements because the contractor has no incentive to design outside the requirements given. There are no defined interfaces at the government-contractor level, which makes simultaneous competition difficult. The intellectual property usually rests with the contractor, which makes competition over time difficult. This is the paradigm that the DoD is attempting to leave, but it has a place in acquisition. For some small, non-complex procurement, it might be the right strategy.

Common Strategy. Common design makes it a little easier to introduce multiple companies, for example, because a government furnished equipment (GFE) process can be used across the common elements of the architecture. One company supplies the equipment, and another uses it in the systems it is developing. However, the common design is “locked-in,” making it very intolerant to changes in requirements. Any changes need to be cascaded through two contract mechanisms, between the government and the GFE supplier, and the contractor building the current system. This increases time and cost.

Interoperable Strategy. The interoperable architecture strategy is intended to allow multiple different products to interoperate. Therefore, it is helpful for lowering barriers to involving multiple companies. However, the interoperable standard needs to be defined at the outset because it defines what aspects of the system must be the same in order to have interoperability. The standard is effectively common and brings the inflexibility, which is both

the strength and the limitation of a standard. The standard is very difficult to update as requirements change, and systems usually ignore the standard and break the chain of interoperability in cases of significant requirements change. Note that changing the standard is not the same as changing other aspects of the elements that interoperate. For example, an aircraft may be upgraded to fly further in response to evolving requirements, but so long as the communication system remains unchanged, the interoperability will remain.

Robust, Flexible, or Adaptable Strategy. These design strategies evolved to allow systems to meet changing requirements, even if the requirements are not known at the time they are developed. Therefore, the strategies score high on the changing requirements axis. However, the principles that are used to evaluate robust, flexible, or adaptable approaches must be applied to the system as a whole, using rigorous system engineering techniques across the entire end product. This makes it difficult to fragment the system and use multiple companies.

Extensible Strategy. An extensible architecture builds in allowances for changes in requirements. However, the changes need to be anticipated at the outset in a way that, for example, a flexible architecture does not. It is difficult to build an extensible architecture without an idea of what will be extended. However, building a flexible architecture, such as a software-defined radio, allows decisions to be made about the changes once the new requirements are better known, for example, writing new software. Whether an architecture is extensible does not appear to have a significant effect on the involvement of different companies in the development of the architecture. Arguably, it makes it slightly easier to include additional companies if the extension can be “re-competed.” However, in many cases, the degree of knowledge of the original contractor about the system makes it difficult for new contractors to be competitive.

Modular Strategy. A modular architecture minimizes the interfaces between parts of a product or system and groups functional areas together. Therefore, a modular architecture is more suitable for the involvement of multiple companies because of the ease of partitioning work packages. A modular architecture also allows aspects of the architecture to be changed out, if necessary, without redesigning the whole system, which makes it reasonably tolerant to changes in requirements.

Open Strategy. An open architecture has low barriers to involving multiple companies. There are fewer intellectual property barriers, and companies are free to submit bids for pieces of work. An open architecture is ideally changed quickly as requirements change because there is a short development cycle due to competition and a minimum of formal requirements. It should be noted that open architectures are heavily dependent on agreed standards to manage the interfaces between the open development and other parts of the system. If the requirement changes necessitate changes in the interfaces and standards, then the benefits of openness to dealing with the requirements change are lost.

The previous analysis suggests that architecting strategies that are chosen largely on “hard engineering” concerns actually have implications for the cost and other programmatics of the project, and the architecting community needs to start coming to grips with which architectures are most useful in which situations. No one acquisitions approach can be universally applied to all architecting strategies. The architecting strategies suit different acquisition scenarios, and therefore, much thought should go into which type of architecting strategy is appropriate for each acquisition. However, due to the overlap of some architecting strategies, more than one strategy may be successful for a given acquisition. Figure 1 highlights where those architectures are more likely to be successful

choices. This underscores Maier and Rechtin's (2009) central thesis that "engineering is more of a science, and architecting is more of an art."

Summary

The terms we have called architecting strategies in this paper—commonality, interoperability, modularity, flexibility, extensibility, robustness, adaptability, and modularity—have all been used at various times as preferred solutions for reducing the cost and schedule of government acquisitions of complex systems.

There has not been a wide and consistent understanding of the full meaning of these terms across the acquisition community. In order to use these terms to communicate approaches and strategies, all personnel involved must share a common understanding of the terminology. Sections I and II of this paper attempted a first step in this direction by surveying the literature and engineering practice to arrive at definitions, strengths, and weaknesses for the architecting strategies. Even with a common understanding of the strategies, a second danger presents itself. That danger lies in a belief that particular architecting strategies are the solution for all acquisitions. In fact, as Section III of this paper showed, some architecting strategies are better suited to particular acquisition scenarios than others. Understanding the interconnections between the architecting strategies and acquisition scenarios is essential to making the right decisions at project initiation. The importance of getting the architecting strategy right, through good communication of ideas and solid understanding of these interconnections, cannot be overemphasized. As Robert Spinrad said, "In architecting … all the serious mistakes are made on the first day" (Maier & Rechtin, 2009). Spinrad was talking about software, but the apothegm applies equally to other forms of complex systems. Better communication and understanding of terminology cannot eliminate mistakes altogether, but they represent a good first step.

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The Joint Program Dilemma: Analyzing the Pervasive Role That Social Dilemmas Play in Undermining Acquisition Success[1]

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Abstract

In the face of both declining budgets and growing interoperability requirements, the military increasingly wants to consolidate multiple needs into single systems to be developed jointly. Unfortunately, the track record for joint system acquisition programs is mixed, and programs often follow a familiar downward spiral:

> The stakeholder programs that depend on a joint system may be skeptical, fearing the needed capability will neither meet their needs, nor be delivered as promised. Stakeholders pressure the Joint Program Office (JPO) to accommodate individual requirements, and the JPO may reluctantly agree, driving up cost, schedule, complexity, and risk—thus realizing the stakeholders' worst fears. These performance issues encourage stakeholders to leave the joint program, potentially rendering it both operationally unattractive and financially infeasible.

This exemplifies a classic social dilemma called the "Tragedy of the Commons." Much work has been done on mitigating social dilemmas, but a solution's success depends on its context. This paper describes the modeling of organizational decision-making in a joint acquisition program using system dynamics. This permits future work to analyze the effectiveness of different social dilemma mitigations within the context of joint programs by using system dynamics.

Introduction

The failure of acquisition programs to deliver high-quality systems within cost and schedule constraints (GAO, 2005)—especially those developing software-reliant systems—is all too common in modern government acquisition. These recurring failures have a direct adverse impact on the ability of the Department of Defense (DoD) to be able to support the warfighter with the systems they need. Delayed systems withhold needed capability, and wasted resources drain budgets that could be used to develop other systems.

The Software Engineering Institute (SEI) has a unique insight into these failures from regularly conducting Independent Technical Assessments (ITAs) on specific programs to determine why they are experiencing difficulties. These investigations have provided visibility into the processes and forces at work within these programs and have produced an understanding of the most common ways that programs come to face serious challenges. Acquisition programs do not fail solely for technical reasons. Organizational, management, and cultural issues are an additional set of significant reasons why acquisition programs may substantially exceed budget, overrun schedule, deliver inadequate quality, and ultimately even fail (Frangos, 1998; Madachy, 2008).

This paper describes research that is being conducted to better understand the joint acquisition program dilemma and to investigate approaches to mitigate associated problems. The general approach is to use a causal loop diagram (CLD) as a means to capture a current understanding of the problem based on past experience in both consulting on joint programs and in conducting ITAs. The CLD embodies an evolving theory of the joint acquisition dilemma that is updated and refined through a series of workshops held with joint program domain experts and decision-makers. The evolving theory is further explored by developing the CLD into a fully executable system dynamics model. Data collected during workshops help to guide, correct, and validate important aspects of the model. When the

model adequately captures the joint program dilemma, it can be used to investigate mitigations to the problem through additional modeling of different mitigation approaches. Ultimately, the most promising mitigations can be evaluated in the workshop context and potentially in pilot tests during the execution of actual joint acquisitions.

The subsequent portions of this paper describe the progress that has been made in conducting this research. The section Social Dilemmas and Joint Programs describes the typical flow of joint acquisition program events. The section System Dynamics Background provides an introduction to the system dynamics modeling approach. The section Workshop with Domain Experts describes the workshops that have been held thus far, and the primary insights gained. The section The Joint Program Simulation Model describes the current state of a system dynamics simulation model refined based on feedback provided during these workshops. Key behaviors exhibited by the model support the hypothesis that joint programs suffer from the "Tragedy of the Commons" social dilemma and that joint program participants may get caught in a trap that can lead to the demise of the program. The section Mitigations for the Joint Program Dilemma describes the space of potential mitigations and solutions to the problems illustrated. Finally, the paper concludes with a discussion of the implications of this work and some future opportunities.

Joint Programs

The category of programs known as "joint" programs constitute a special case within DoD acquisition. Such programs intend to provide a system, subsystem, or capability that will fulfill needs of, and be funded or managed by, more than one DoD service or component. Joint programs are appealing because they offer at least two significant potential benefits: (1) reducing costs by developing one system as opposed to several differing ones and (2) improving interoperability by providing a single system or capability that can be used for multiple purposes in multiple contexts. Joint programs are recognized as being difficult to manage because they have multiple stakeholder programs intending to use the joint capability (often with differing needs), they may be larger in size than other programs, they may be more complex organizationally, and they may be geographically dispersed—all causing increased levels of coordination, communication, and negotiation overhead. At the same time, joint programs are becoming increasingly important to the military as the need for interoperability grows and as there is greater pressure on the overall defense budget to reduce costs.

Although the focus of most acquisition programs is on the complex system being developed, it may be overlooked that acquisition programs themselves, especially joint programs, are complex, dynamic systems—and as such can display unpredictable and even seemingly chaotic behavior. This results from the presence of *feedback* between the autonomous actors populating different groups within the acquisition organization. Feedback in the system produces non-linear behavior, where changes in the system's outputs may no longer be proportional to changes to the inputs. The complexity of this feedback, inherent in any system involving interacting human beings, coupled with time delays between inputs and outputs that obscure the relationships between cause and effect, can produce unexpected behavior in even simple systems. Such systems must be analyzed as a whole in order to understand their behavior, because the problematic behaviors often emerge directly as a result of these interactions—and vanish when the system is decomposed into its component pieces for study.

Misaligned Incentives in Acquisition

It has been concluded in studies (Kadish, 2006; Pennock, 2008) that the incentives at work in acquisition policy and governance are often misaligned. These misalignments can

cause a disconnect between the desired outcome and the most promising ways of achieving that outcome. The result of misaligned incentives can be shortsighted acquisition decision-making, potentially putting short-term interests ahead of longer term interests, or individual and program interests ahead of PEO and service interests, thus turning planned cooperation into opposition.

Many of the misaligned incentives seen in acquisition belong to a category of problems known as social dilemmas. Social dilemmas are ubiquitous across human organizations. They describe situations in which the incentives align to promote a solution by the actors involved that may be locally optimal but will be suboptimal at a more global level.

One common type of social dilemma is called a "social trap" (Cross & Guyer, 1980; Kollock, 1998). In a group context, a social trap means that an individual desires a benefit to himself that will cost everyone else—but if all in the group succumb to the same temptation, then everyone is worse off. A social trap is often referred to colloquially as a "Tragedy of the Commons"[2] (Hardin, 1968). What is noteworthy about this dilemma is that there is no intent to destroy the common resource—it's the combined actions of all acting in their own self-interest that lead to the tragic result.

Social dilemmas come in many different forms, with many different properties, which helps to make them both difficult to recognize and difficult to fix. The next section outlines social dilemmas in the context of a joint program.

Social Dilemmas and Joint Programs

Joint programs are noted for the unique challenges that they face organizationally (Lindsay, 2006), due in part to the tension between the individual programs and services needing to look out for their own interests and the Goldwater-Nichols Department of Defense Reorganization Act of 1986 that stresses the importance of all service branches working together both effectively and efficiently. Because of this seeming paradox, there is a fundamental social dilemma at the heart of every joint program that can be seen in the following narrative, which summarizes the experiences of a number of joint and joint-style programs that the SEI has worked with:

> A joint program has six stakeholder programs all planning to integrate the joint infrastructure software that is being developed to meet a common baseline set of requirements. However, each stakeholder program then also requests that one or more significant new requirements be added to satisfy some custom needs of that specific stakeholder program. Although reluctant, the joint program manager agrees to the new requirements out of fear of losing stakeholder programs, who might leave the joint program to build their own custom software. As development proceeds, the additional requirements and their resulting design changes and incremental development significantly increase the total cost, schedule, complexity, and risk of the joint development effort. As the schedule begins to slip, one stakeholder program realizes that the joint program has put the stakeholder in danger of missing its own schedule, and so it leaves the joint program to develop its own software.

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[2] The original story of the "Tragedy of the Commons" from the 19th century envisions a group of herders sharing an area of grazing land called a commons. If one herder decides to graze an extra animal, then that herder receives more benefit from the commons than the others, and at no additional cost to himself. However, if all of the herders follow suit and add more animals according to the same reasoning, they eventually reach the point where the grass is eaten faster than it can grow, the cattle begin to starve, and ultimately all of the herders lose their livelihood.

> Although one stakeholder program has left the joint program, the incremental cost of the more complex architecture that was designed to support the stakeholder's desired capability cannot be recouped. The schedule delays from the increased complexity and risk impact the remaining stakeholder programs as well, and soon another stakeholder program chooses to leave the joint program. Exacerbated by the effort spent in re-planning the joint effort each time a stakeholder program leaves, costs continue to escalate, and the development schedule lengthens. The remaining stakeholder programs begin to reconsider their participation in the joint program, and ultimately participation unravels and collapses.

With this narrative in mind, a joint program can be viewed as a "Tragedy of the Commons" in which the commons is the development resource of the joint program office and the contractor. The entire program and the stakeholder programs are collectively worse off if the stakeholder programs choose to exploit the development resource for their individual gain by insisting on having custom requirements developed.

It is important to note that a "Tragedy of the Commons" situation does not always occur in a joint program. It may be the case that strong leadership from the joint program manager, or a highly cooperative culture within the program, will prevent it from happening. However, given the fact that the incentives align to favor unilateral action by the stakeholder programs and their services, unless specific preventative steps are taken, preventing this social trap is more likely to be the exception rather than the rule.

The next section provides context for the creation of a system dynamics model of this behavior.

System Dynamics Background

The system dynamics method helps analysts model and analyze critical behavior as it evolves over time within complex socio-technical domains. A key tenet of this method is that the dynamic complexity of critical behavior can be captured by the underlying feedback structure of that behavior. The boundaries of a system dynamics model are drawn so that all of the enterprise elements necessary to generate and understand problematic behavior are contained within them. The method has a long history, as described in Sterman (2000) and Meadows (2008).

System dynamics and the related area of systems thinking encourage the inclusion of "soft" factors in the model such as policy, procedural, administrative, and cultural aspects. The exclusion of soft factors in other modeling techniques effectively treats their influence as negligible, which is often an inappropriate assumption. This holistic modeling perspective helps identify mitigations to problematic behaviors that are often overlooked by other approaches.

Figure 1 summarizes the notation used by system dynamics modeling. The primary elements are variables of interest, stocks (which represent collection points of resources), and flows (which represent the transition of resources between stocks). Signed arrows represent causal relationships, where the sign indicates how the variable at the arrow's source influences the variable at the arrow's target. A positive (S) influence indicates that the values of the variables move in the same direction, whereas a negative (O) influence indicates that they move in opposite directions. A connected group of variables, stocks, and flows can create a path that is referred to as a *feedback loop*. There are two types of feedback loops: balancing and reinforcing. The type of feedback loop is determined by counting the number of negative influences along the path of the loop. An odd number of

negative influences indicates a balancing loop; an even (or zero) number of negative influences indicates a reinforcing loop.

Significant feedback loops identified within the model described here are indicated by a loop symbol and a loop name in italics. Balancing loops—indicated with the label *B* followed by an identifying number in the loop symbol—describe aspects of the system that oppose change, seeking to drive variables to some equilibrium goal state. Balancing loops often represent actions that an organization takes to manage, or mitigate a problem. Reinforcing loops—indicated with a label R followed by a number in the loop symbol—describe system aspects that tend to drive variable values consistently either upward or downward. Reinforcing loops often represent the escalation of problems but may include problem mitigation behaviors.

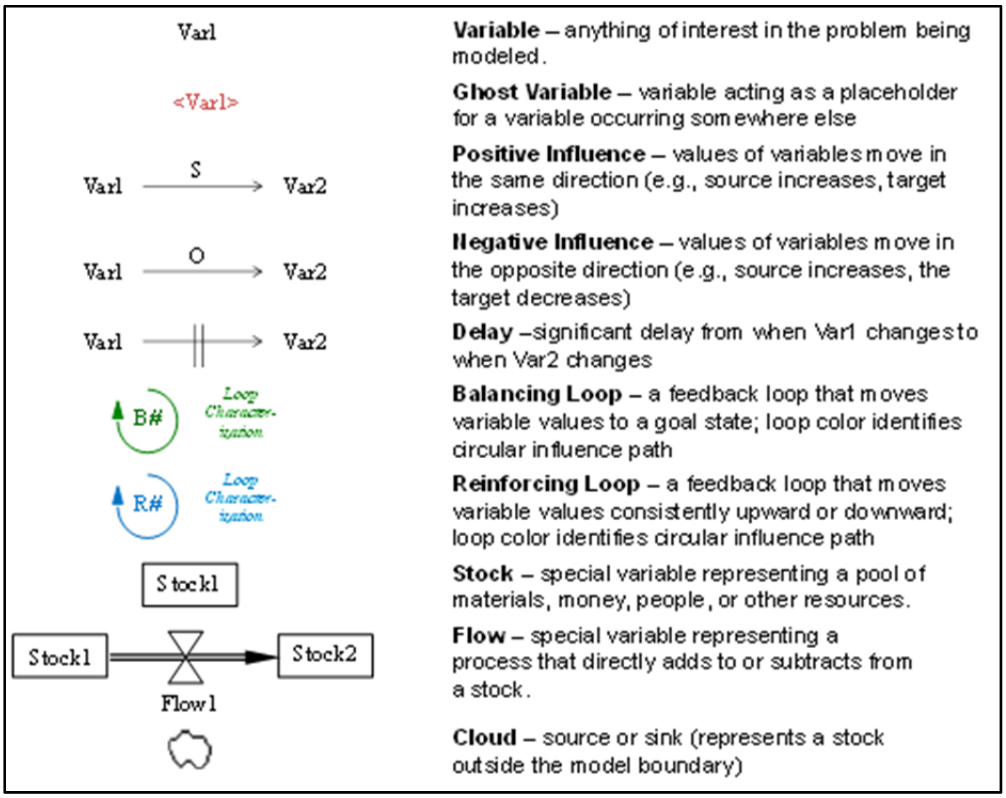

Figure 1. System Dynamics Notation

The next section discusses how the system dynamics modeling process was used to elicit a detailed understanding of joint program behavior from subject matter experts.

Workshop With Domain Experts

A series of *problem elaboration workshops*[3] is being used as the primary method for gaining feedback from acquisition subject matter experts on the current system dynamics model, and for eliciting suggestions for additional potential improvements. To date, a shortened pilot version of the problem elaboration workshop has been conducted with

[3] These workshops are covered by the Carnegie Mellon University (CMU) human subject research policy, and protocol HS12-237 for conducting these workshops has been approved by the CMU Institutional Review Board (IRB). Nothing discussed at the workshops is tied to a specific individual or organization.

internal SEI acquisition experts as well as a full two-day workshop with program office and contractor personnel from a single joint program.

The problem elaboration workshops are intended to consist of personnel drawn from a single joint program. Ideally each workshop will include a mix of program management and technical personnel as well as personnel from both the acquirer and developer side. The workshops last approximately two days in order to cover a substantial portion of the relevant material. The top-level causal loop diagram of the dynamic is reviewed as a high-level abstraction of the model because reviewing the entire system dynamics model is not feasible for the acquisition subject matter experts.

There are two primary goals for each problem elaboration workshop: (1) discuss the current top-level loops in the model causal loop diagram and have the participants rate the importance and accuracy of each loop using a Likert scale and (2) gain insight from the participants on any loops/interactions that may have been overlooked. The initial workshop focused on a joint program designed to provide a joint communication capability needed by several services that was to be deployed on a number of different platforms to allow for effective communication between platforms belonging to multiple services. The participants included personnel who had worked at the government program office and personnel from the prime contractor. The workshops were effective in achieving their goals, and some of the results are summarized as follows.

Goal 1: Rating the top-level loops. After presentation and discussion of all of the top-level loops in the CLD of the large model (see Table 1 in Appendix A for high-level descriptions of those loops and Figure 11 in Appendix B for a graphical depiction), ratings were obtained from all participants. Nine of the 12 loops in the CLD (75%) were rated above moderately important. In seven (i.e., 58%) of the loops, the average accuracy score was rated above moderately accurate. Of these seven loops rated above moderately accurate, four of these loops (33% of the original 12) were rated above very accurate. For all 12 loops, at least one of the four participants rated themselves as extremely experienced in this area, and all loops had at least two participants who rated themselves as very or extremely experienced. Based on the feedback from the participants, one section of the CLD that scored lower in importance was modified in order to change how stakeholder programs may influence others to defect, or leave the joint program.

Goal 2: Overlooked loops/interactions. The workshop participants discussed nine additional interactions that they thought had been important on their joint program. The top area they thought should be added addressed launching the program properly. The model was modified to address this area, and additional ways of implementing this concept are being explored. A second area that was identified as needing to be addressed is the level of capability of the government staff, and this has been added to the model as well.

Feedback from actual program personnel is critical to ensuring that the model includes the most important top-level interactions. It is also critical to tuning the model parameters to best simulate the performance of joint programs. Additional problem elaboration workshops are planned for the near future to continue to refine the model.

The Joint Program Simulation Model

As described previously, the problem elaboration workshop attendees were presented with a CLD that already described many aspects of joint program behavior. The feedback from these domain experts made it possible to assess the most important aspects of the joint program problem, many of which were included in the original CLD and some of which were not. This information was used to develop a simpler and more focused CLD that better represents the inherent social dilemma and other central aspects of the joint program

dilemma as seen by the workshop participants. Appendix B contains this refined CLD.[4] As additional workshops are conducted, other aspects may be included or excluded from the CLD based on the findings of those workshops.

The only loops retained in this simpler model are the stakeholder custom requirements acceptance (B3), pressure-induced rework (R3), and pressure-induced attrition (R4), as described in Appendices A and B. The first two of these were the top two rated feedback loops at the workshop. The third, which is closely related to the second, occurs in most joint programs and causes significant turmoil and lost productivity. Also included is one of the two highest rated extensions proposed to the original model: The inclusion of Joint Program Office (JPO) efforts to keep the joint program sold to stakeholders was deemed a key contributing factor to endemic problems and inefficiencies. The top-rated extension that was suggested at the workshop, the distinction between acquiring capabilities as opposed to acquiring systems, will be addressed explicitly in future versions of the model.

The system dynamics method provides a way of implementing a CLD, so as to further explore the implications of the causal structure as it is elaborated in more detail. These implications are assessed through simulation (execution) of the model. In addition to the confidence gained in the CLD during the workshops, simulation can result in additional confidence that the causal structure can indeed produce the behavior implied by the qualitative CLD. Once the model has been shown to exhibit the expected behavior, workshop interactions can help ensure that it does so for the correct reasons. This level of validation then allows the analyst to use the model to test alternate solutions to the problem using the system dynamics simulation capability.

The simulation and analysis of the joint program model is still ongoing, and it is the initial results of that effort that are presented here. The feedback that was received in the initial problem elaboration workshop made it possible to simplify and focus the original simulation model that had been developed. The three primary segments of the current simulation model are described in order: the Stakeholder Program Segment, the Joint Program Office (JPO) Segment, and the Developer Segment. Each of the stakeholder programs, the JPO, and the developer have reasons to be at least comparatively satisfied based on the progression of events thus far, early on in the joint program acquisition. However, as will be seen in the subsequent section, Systemic Effects, their relative satisfaction will be spoiled due to the diminishing returns associated with joint program expenditures.

- The current model makes the following assumptions about the joint acquisition program:
- The timeline of the simulation is 120 months—10 years—but the conclusion of the project may be significantly short of that, and vary depending on the input parameters. Milestone B occurs 12 months into the simulation, and that is when the development contract is awarded.
- The joint program has three stakeholder programs that negotiate with the JPO for their own custom requirements separate from a set of baseline requirements. The stakeholder programs are referred to abstractly as S1, S2, and S3.

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[4] Note that CLDs and system dynamics models share a similar notation. The primary difference is that CLDs do not include stocks or flows. They are strictly qualitative and so are not executable.

- Funding for the joint program is spent strictly on development activities. JPO staff can rotate out and be hired in, but the staff levels stay at generally the same level and do not consume funding (e.g., they are on overhead, as far as the model is concerned).
- Developer staff are separated into new staff versus experienced staff, each with their own levels of productivity (i.e., computer software configuration items (CSCIs)[5] developed/tested per month) and monthly costs. Experienced staff may have their time partially consumed by training new staff.

These assumptions may be relaxed in future revisions to the model to allow a broader range of behaviors to be tested.

It should be noted that although the model described as follows has been refined both by the problem elaboration workshop sessions and through the acquisition experience of the modeling team itself, this model has not yet been validated with historical joint program data to help quantify the relationships between the model variables. This validation will be conducted, but at this point, the model should be viewed as providing only tentative support for the causal hypothesis.

Stakeholder Program Segment

A primary concern of the stakeholder programs is getting their (custom) requirements implemented by the joint program so that they have the most usable system possible when the joint program completes development. There is a fair amount of negotiation going on during these times between the joint program office and the stakeholder programs, and the initial model is based on the foundations of negotiation and cooperation theory. Other work in developing system dynamics models has leveraged some of this theory in the past. This model is based explicitly on models developed by Darling and Richardson (1990).

As illustrated in Figure 2, stakeholder program decision-making is based on the following:

- *Stakeholder program gain* (the inner loop in the figure). The extent to which the stakeholder program's custom requirements are implemented in the joint system. In terms outlined by Darling, this gain limits the stakeholder program's problem potential. An effect function[6] is used to capture the framing effects of Darling's model, which is used to determine whether the extent of the stakeholder program's gain is viewed positively or negatively.
- *Stakeholder program's relative gain (the outer loop in the figure).* The stakeholder program's satisfaction is also dependent on how much they perceive others are gaining relative to their own gain. If they think others are getting proportionally more, then they will be less satisfied even if they are still getting their own needs met adequately. This is a refinement of Darling's model, which was based on a weighted sum of the gain for self and the perceived gain of other stakeholder programs.
    - A more recent perception of gains weighs more in stakeholder program decision-making than older perceptions. This relates to the moving average used in the Darling model, which models how past outcomes influence present expectations.

[5] A CSCI is a collection of software that supports a specific function for the end user.
[6] An effect function is a device used in system dynamics modeling that explicitly describes the mathematical relationship between two specific model variables over time.

- The possibility that a stakeholder program may have only a limited understanding of other stakeholder programs' gains (Darling's "Fixed Pie Bias") is handled with a weighted formula. To the extent that understanding is incomplete (i.e., knowledge of other's gain is less than 1), a stakeholder program assumes that their loss is the other stakeholder program's gain.

Initial discussion with joint program decision-makers suggests that concern for fairness, as described in Darling's model, is not a primary factor in stakeholder program decision-making, so it has been omitted from the simplified model presented here. It is, however, still a factor in the larger model being developed.

A stakeholder program's satisfaction influences both the extent of their buy-in to the joint program and their cooperation with the joint program goals. Both buy-in and cooperation with the joint program are needed to keep the program viable. When either is lagging, the JPO will tend to implement more of the stakeholder program's custom requirements to keep the stakeholder program engaged.

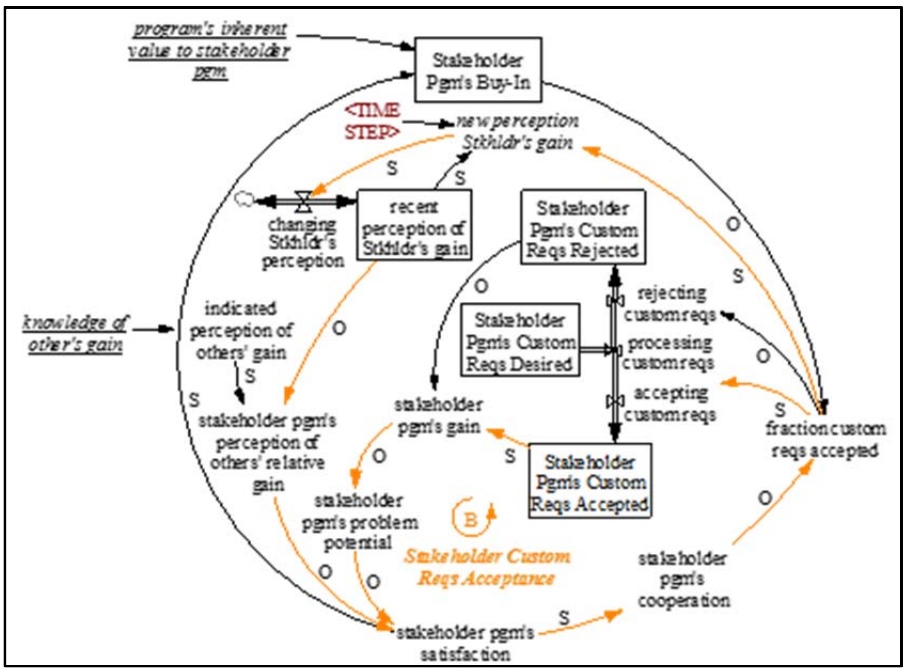

Figure 2. Stakeholder Programs Negotiate for Custom Requirements Beyond Baseline

This effect can result in an escalation of custom requirements, which of course must then be integrated with the original requirements. The model initial settings are set to an equilibrium. At Month 18, to test the behavior of the model, the demands of stakeholder S1 are stepped up to a level of 0.8 on a scale of 0 to 1. This perturbation from equilibrium shows in Figure 3 that increases in one stakeholder program's demands leads to increases in other stakeholder programs' demands. Although the levels do not rise to the same degree, the escalation of custom requirements that result are necessary from the joint program perspective in order to maintain stakeholder programs' buy-in and prevent stakeholders from defecting.

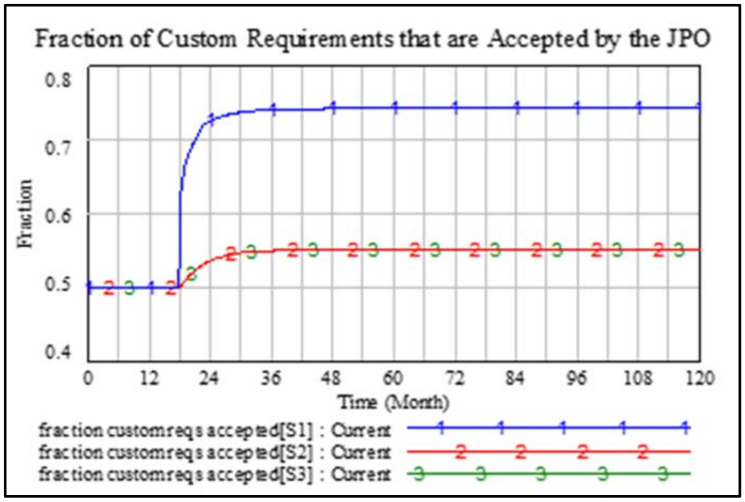

Figure 3. Increase in Custom Requirements Acceptance for S1 With Subsequent Rise for S2 and S3[7]

In the Darling model, this behavior reflects the "competitive drift" possible, where one negotiator is pitted directly against another and the interaction between negotiators becomes increasingly acrimonious. In the joint program case, the JPO may feel compelled to give in to stakeholder program demands across the board, directly supporting the creation and reinforcement of the underlying social dilemma. With greater support being given to their individual needs, the stakeholder programs remain relatively satisfied.

Joint Program Office (JPO) Segment

The benefit of keeping stakeholder programs "bought in" to the joint program is evident in Figure 4. More engaged program stakeholders promote DoD buy-in. Once the development starts, especially with the additional custom requirements accepted, plus-ups on funding and extensions to the schedule are usually necessary to implement the additional functionality.

[7] This and subsequent graphs were generated using the Vensim modeling tool. These are all behavior-over-time graphs, and as such, the x-axis for these graphs is specified in months (120 months—10 years—is the duration of this simulation). Each simulation run is specified as individual graphs distinguished with a number label (1 through 3 in Figure 3), as specified in the legend below the graph.

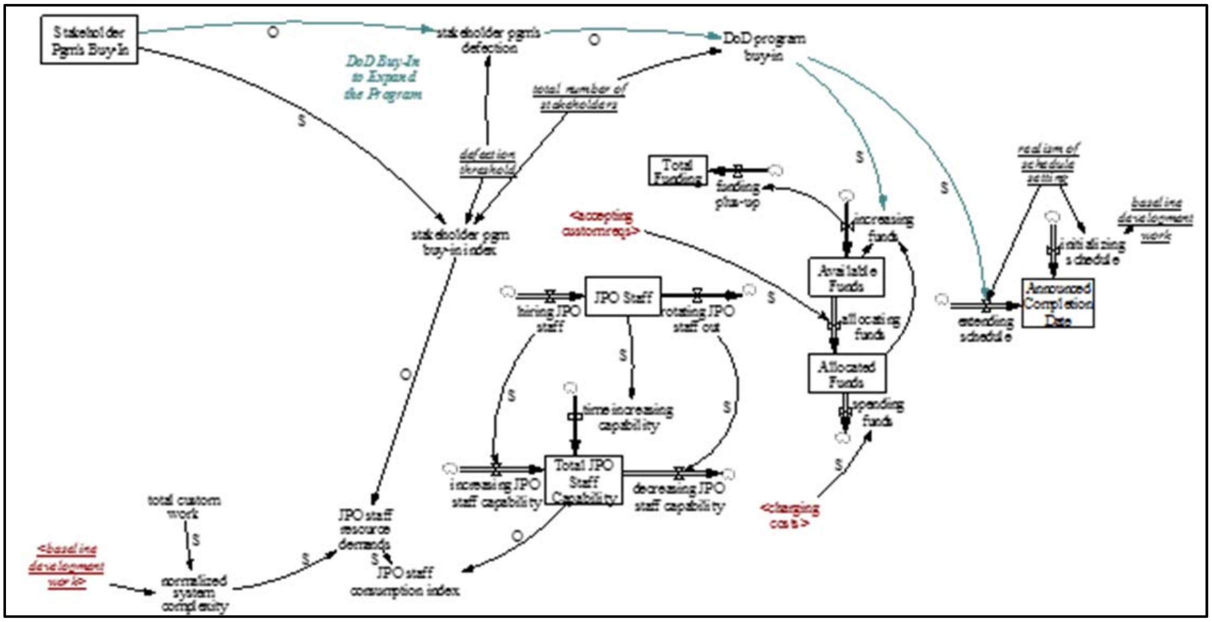

Figure 4. JPS Benefits From Increased Stakeholder Program Buy-In by Keeping the Program Alive

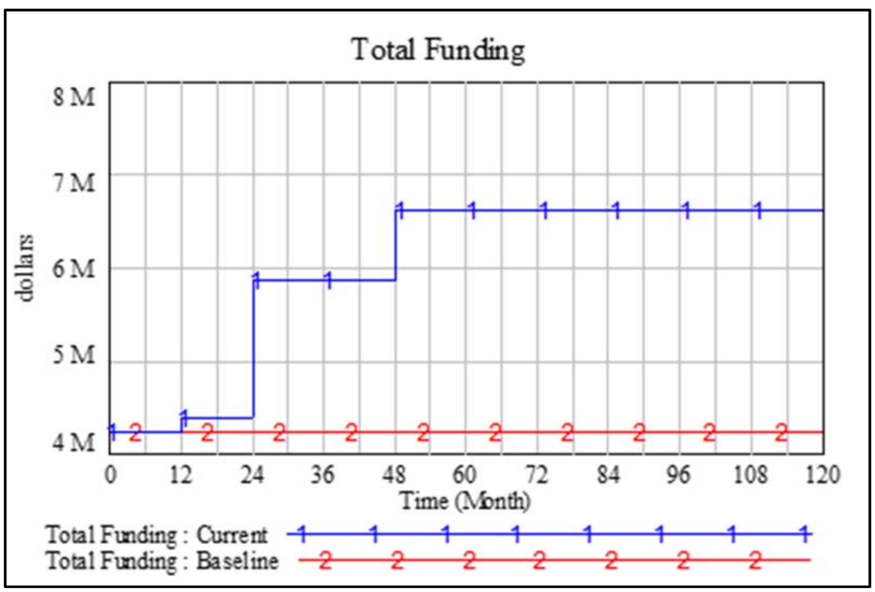

Figure 5. Additional Funding Increments to Implement Expanded Scope

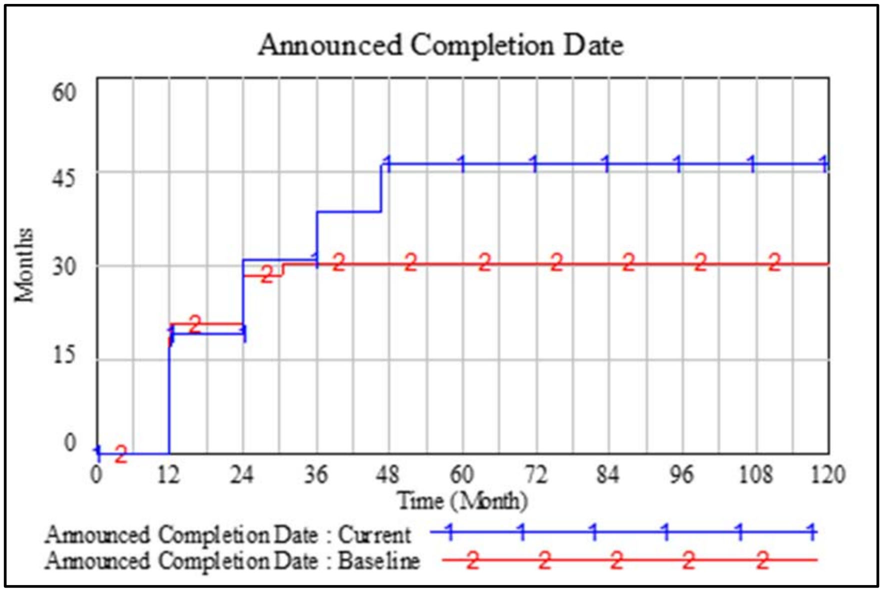

Figure 6. Additional Schedule Extensions to Implement Expanded Scope

Developer Segment

The additional development work generated due to the additional custom requirements from the stakeholder platforms is shown in the middle of Figure 7. This additional development work, along with the development work from the originally planned baseline, is added to the development work remaining. Both development and testing work is accomplished based on the productivity of the development staff, shown on the left side of the figure.

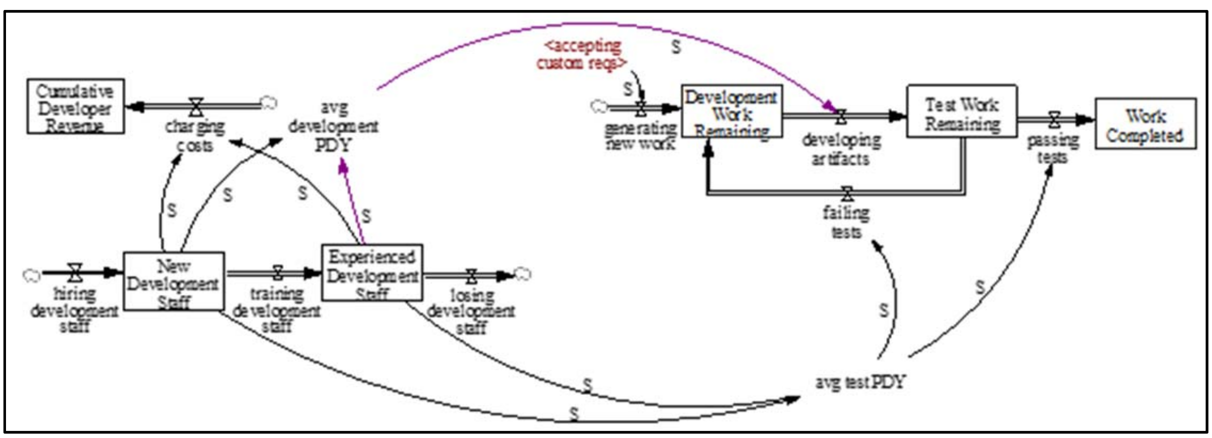

Figure 7. Development Staff Managed to Complete Development Work

Development staff is split between new hires and experienced staff, with some training period (possibly on-the-job) needed to transition from new to experienced. The development productivity levels of new and experienced staff differs, with experienced staff spending some of their time training the newer staff. All charges made by the staff for their time working on the project are reflected in the cumulative contractor (i.e., developer) revenue. As shown in Figure 8, the contractor's revenue rises well above the baseline levels, partially due to implementing the additional custom requirements demanded by the stakeholder programs. In this context, assuming that the contractual negotiations are

providing additional revenue for the additional employees, the contractor is willing (if not even happy) to employ more staff for a longer period.

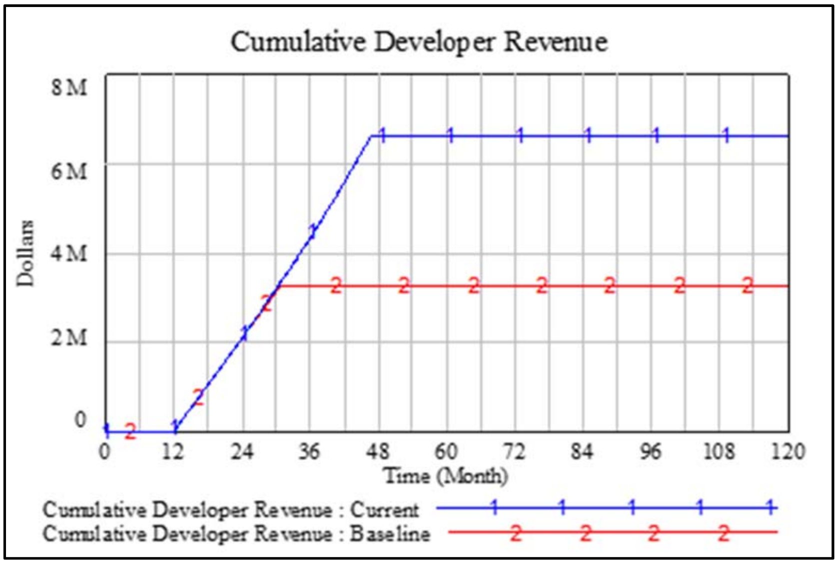

Figure 8. Developer Revenue Rises Well Above the Baseline Level[8]

Systemic Effects

Although the stakeholder programs, the JPO, and the developer accomplish important objectives in their own domains, these objectives act as a trap for joint program decision-makers that can potentially lead to the demise of the joint program. Figure 9 shows the diminishing returns related to the joint program investment to develop the extended joint system. As the number of custom requirements accepted for each stakeholder program increases along the x-axis, the average cost per CSCI increases by a factor of 5 to 10 over the average cost per CSCI in the baseline development. Another dimension, along the z-axis, shows that as the realism of schedule setting decreases from 1 to 0.1, the CSCI cost ratio declines even further. As a result of the simulation and analysis of this scenario, representations of complex decision surfaces such as shown in Figure 9 allow decision-makers to understand the interactions between multiple factors within a system, and to understand the range of possible outcomes based on various actions.

[8] Development is complete about Month 30 in the Baseline simulation run and about Month 47 in the Current run.

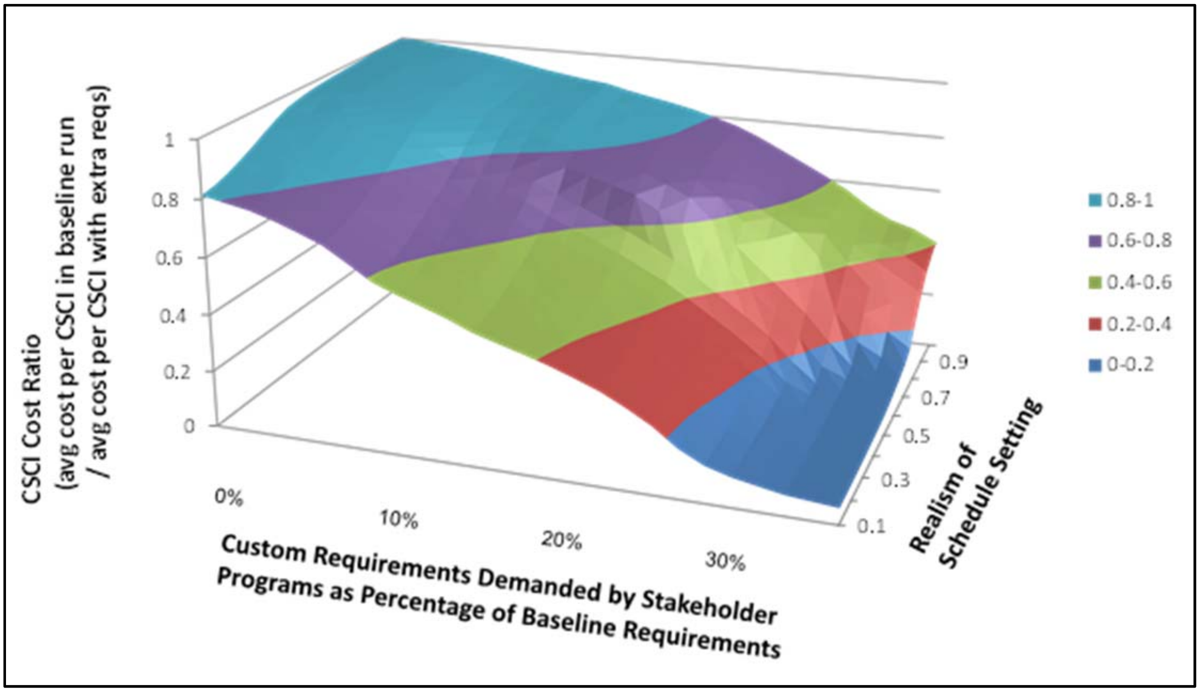

Figure 9. Systemic Result: Diminishing Returns in Development Effort Lead to Cost Increases for Program

The overview model, shown in Figure 10, integrates the stakeholder program segment, the JPO segment, and the developer segment described previously. The model also illustrates the primary influences causing the diminishing returns:

- *Complexity-Induced Rework* (in blue in the lower middle of the figure)—The system complexity that results from program stakeholder custom requirements decreases average development productivity and increases the rates of defect injection during development. The increased system complexity increases the complexity of developing individual CSCI for a variety of reasons, making development take longer and be more error prone.
- *JPO Staffing Effects on Program Execution* (in green in the lower middle of the figure)—The resource demands on the JPO staff, as described previously in the JPO segment, causes two primary problems for the developers. First, the JPO staff is not as responsive to developer demands for guidance, and for review and feedback on development artifacts. This reduces the average developer productivity. The second effect is that the JPO staff shortcuts the quality of their guidance and review process. This leads to lower quality in the development, and greater amounts of rework.
- *Pressure-Induced Rework* (the red reinforcing feedback loop)—The expansion of the joint system scope leads to the need for extensions to the schedule well beyond those planned for the original baseline system. Although the need for schedule extensions is widely recognized, they may come infrequently at unpredictable times, and only if decision-makers remain adequately bought in. The result is intense schedule pressure, which may be evident even early in the program if the initial schedule was unrealistic. Such schedule pressure can lead to bypassing some quality processes, and to the

generation of higher levels of rework. This acts in a reinforcing manner as schedule pressure escalates even further.

- *Pressure-Induced Attrition* (the purple reinforcing feedback loop)—Development staff may suffer the most from schedule pressure. When development staff are in high demand, attrition may grow. Despite new development staff being hired, the average and thus the overall productivity may fall, making it even harder to meet schedule demands. This reinforcing dynamic exacerbates the problem further.

This section described the hypotheses about why joint programs can get trapped into a development of diminishing returns. The four causes for these diminishing returns, described previously, provide a view of what can go wrong. Mitigation of this problem may involve developing a means to avoid falling into the trap in the first place or for reducing the negative consequences associated with falling in the trap. The next section describes some of the considerations regarding problem mitigation.

Mitigations for the Joint Program Dilemma

The rationale for identifying a possible inherent social dilemma at work within the structure of a joint program is to understand the mechanism by which these types of acquisition programs can encounter difficulties. Once the mechanism has been confirmed, there is a large set of mitigations and solution approaches that have been developed in different academic disciplines such as game theory, behavioral economics, social science, and social psychology, with each addressing differences in the specifics of the instance of the dilemma. Elinor Ostrom received the 2009 Nobel Prize in Economics for her study of innovative solutions that have evolved in different cultures to address differing instances of the "Tragedy of the Commons." However, these academic solutions are not well known to the software-intensive acquisition or software development communities and thus have not yet been studied in the context of acquisition programs, so their applicability is still unknown. The goal, however, remains the same—to deploy higher quality systems to the field in a more timely and cost-effective manner.

The research literature organizes the solutions to social dilemmas such as the "Tragedy of the Commons" into three classes:

- *Motivational*. Motivational solutions assume that participants are not exclusively self-interested and thus care about the consequences of their actions on other participants. Because of this, such concerns as values and group identity, as well as communication, can be effective.
- *Strategic*. Strategic solutions assume that participants are exclusively self-interested and so require that the participants influence how the other participants behave, thus producing a better outcome for themselves. Robert Axelrod (1984) provided three ingredients for such approaches: (1) long-term relationships among the participants (so that all expect shared dilemmas in their future), (2) that the participants can identify one another, and (3) that participants are aware of the past behavior of each other.
- *Structural*. Structural solutions require changing the rules of the situation so that the nature of the dilemma also changes. The most significant difficulties with applying structural solutions is that (1) they require a level of authority to implement, (2) they may bring about resistance from those who are affected, and (3) they require methods (with accompanying costs) to ensure compliance with the new rules.

The first two classes (i.e., motivational and strategic) do not require changing the fundamental structure of the situation, and as a result, they tend to be simpler to implement—although their effectiveness is less certain when compared to a structural solution.

To discuss one common approach to resolving a social trap,[9] the use of an *authority* to manage the commons is widely used in practice. However, this approach may have side effects, depending on how the leader was selected and from which organization, since the perceived objectivity and neutrality of the leader is essential to their acceptance by the participants.

Another widely used approach is *privatization*, which, like the use of authority, also has side effects. By removing the social aspect of the social dilemma, it eliminates the interdependence between people by converting shared ownership to private ownership. However, this would result in each of the stakeholder programs building their own custom system, which is antithetical to the originally intended outcome.

Another approach that could produce a better outcome might be altruistic punishment (Fehr & Gachter, 2002). In *altruistic punishment*, cooperating participants may penalize uncooperative participants through some mechanism (such as withholding a small funding increment) at a small cost to themselves. Participants seem willing to do this, despite the cost—and even if it will yield no direct material gain to them. Fehr and Gachter's research indicated that cooperation increases if altruistic punishment is possible and may break down if it is ruled out. In addition, imposing a cost on the administering party disincentivizes overuse, making it self-correcting.

Such a solution could help to avoid the requests for additional capabilities and prevent the downward spiral due to a lengthening schedule and increasing cost, complexity, and risk, thus incentivizing stakeholder programs to stay with the joint program, rather than defect. However, this particular solution to the social trap may or may not be feasible for use on a joint program.

Another way of addressing a social trap would be a strategic approach: making a series of small changes to the incentive and reward structure of the program, such as improving communications, making negative behaviors more visible to all participants, and similar modifications. Although no single such change would be likely to significantly mitigate the problem, it may be that the aggregate effect of many small changes to the program structure, when taken together, could have a substantial positive impact.

Other solutions to addressing social dilemmas exist, such as building trust, exclusion mechanisms, assurance contracts, and many others. The choice of the best solution will depend on the specific circumstances surrounding the specific joint program dilemma.

The defense acquisition system itself poses some significant challenges to successfully mitigating the types of problems that are inherent to joint programs and common infrastructure programs. When looking at the structural, strategic, and motivational classes of solutions to social dilemmas, it is apparent that motivational solutions, while attractive due to their generally lower level of effort to implement, may have little ability to effect change if the participants have substantial self-interest. The knowledge that "the complicated acquisition system generates staggering bargaining and coordination costs" such as "bureaucratic politics including inter-service rivalry, Joint service logrolling" (Lindsay, 2006) make a belief in the services having low levels of self-interest seem unlikely. Strategic solutions are more pragmatic but rely largely on the reputation of individuals and longer term

[9] Social traps were discussed in the section Misaligned Incentives in Acquisition.

relationships between negotiating parties, both of which are in short supply in a military where “the average tenure for program management in DoD is only 18 months” (McConnell, Sickler, & Yang, 2004). Structural solutions thus may appear to have the most promise of the three classes, although convincing all of the authorities required both to implement and enforce new rules on all parties in a joint program context may prove to be problematic.

The research with the system dynamics model of joint programs that is being developed involves the selection of some of the most promising mitigation and solution approaches, and modeling those approaches in the context of the joint program model. By assessing the ability of these solution approaches to mitigate the key adverse dynamics that are often present in joint programs, it will be possible to identify a set of the most promising approaches that could be applied in practice to try to avoid these issues in an actual joint acquisition program.

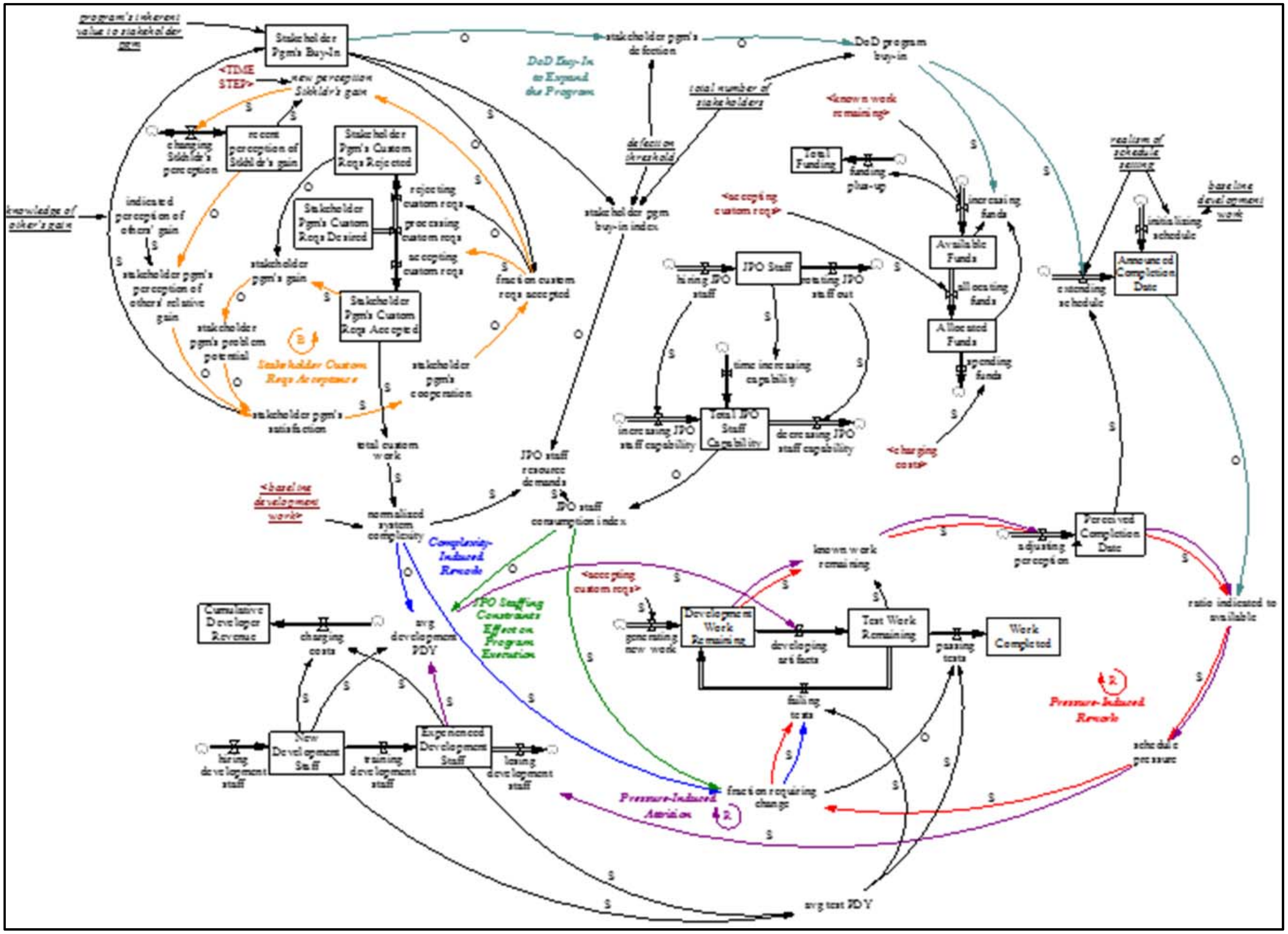

Figure 10. Simulation Model for Joint Acquisition Program Dynamic

Future Work

Some of the possible areas for future work will involve additional refinement and validation of the simulation model through review and feedback by joint acquisition domain experts, as well as calibration with historical program performance data. Once sufficient confidence in the model is gained through validation, it can be studied further to understand how the different key model variables are interrelated, and contribute to the causes of problematic behaviors. Complex surfaces, such as the one shown in Figure 9, can be created to give a sophisticated understanding to decision-makers as to how multiple variables interrelate and interact. The model can thus be used as a management decision aid to gain an understanding of what might occur in the future if current conditions continue unchanged and to explore hypothetical "what if" scenarios based on potential decisions and events. As the work proceeds, candidate motivational, strategic, and structural mitigations to the problematic dynamics of the joint program social dilemma will be developed and simulated to assess their effectiveness and viability, and to help develop potential new approaches and even policy recommendations to help improve the execution of these types of programs.

Although no model can accurately predict with consistent accuracy the future states of a complex dynamic system such as an acquisition program, Donella Meadows (1974) pointed out that "this level of knowledge is less satisfactory than a perfect, precise prediction would be, but it is still a significant advance over the level of understanding permitted by current mental models."

Conclusion

This paper describes the results of a preliminary investigation into the problems encountered by joint acquisition programs. Through interaction with joint acquisition experts, decision-makers, and stakeholders, a CLD now exists that represents a refined understanding of the problem. The CLD embodies a growing comprehension of what happens in joint acquisition programs and why the stakeholder programs, the JPO, and the developer can become trapped in behaviors that make rational sense to the participants at the time but can lead to diminishing returns and potentially failure for the program. It describes the inherent social dilemma that exists within joint programs—and provides the basis for a better understanding of the problem and for developing ways of mitigating it to minimize future joint program challenges.

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Appendix A: Feedback Loops Discussed in Workshop

Table 1. Loops of the Original CLD Discussed at the Problem Elaboration Workshop

Loop	Name	Description
R1	Stakeholder Bandwagon	Low stakeholder satisfaction can lead to a desire to defect, as well as attempts to influence other stakeholders to defect, causing a vicious cycle that can collapse the joint program.
B1	Membership Management	Lack of stakeholder support can lead to low service support, especially if the program's value to the service is low. This may require a greater "marketing" effort by the JPO to sustain stakeholder support.
B2	Program Support	Lowered service support can undermine DoD support, requiring still more JPO "marketing" effort to keep the stakeholders engaged.
R2	Stakeholder Confidence in JPO	Stakeholder support can grow as the progress of the grogram adheres to the schedule set forth. However, if the program falls behind schedule, stakeholders may become dissatisfied, start to lose confidence, and ultimately even defect.
B3	Stakeholder Custom Requirements Acceptance	Stakeholders are especially concerned with meeting their own custom requirements. To the extent those requirements are not addressed, the stakeholders may insist, and the JPO may eventually need to accept their requirements.
B3b	Stakeholder	As more of a stakeholder's custom requirements are accepted, fairness to others may

	Concern for Fairness	come into play. The stakeholder may become more cooperative, lowering his/her demands for more custom requirements.
B4	Honey Rather than Vinegar	The JPO may resist accepting custom requirements if the stakeholder becomes too demanding. The stakeholder may then reassess, becoming more cooperative if he thinks more of his custom requirements will be accepted.
R3	Pressure-Induced Rework	Accepting custom requirements leads to expanded program scope. Without schedule relief or additional staff, this puts additional pressure on workers, potentially causing them to bypass quality processes, thus resulting in more rework.
B5	De-scoping	To reduce schedule pressure and try to get development back on track, the JPO may eliminate requirements or defer them to a later development phase.
R4	Pressure-Induced Attrition	If sustained, excessive schedule pressure can disgruntle developers, leading to attrition, and making it even harder to meet schedule demands.
R5	Stakeholder Missing their Schedule	Delaying the schedule past the stakeholder’s need date for the capability increases dissatisfaction, and can be a primary cause of defection.
R6	Stakeholder Escalating Costs	Expanding project scope can lead to greater shared costs to each stakeholder. This may increase discontent and lead to greater demands to meet custom stakeholder requirements, especially early on.

Appendix B: Simplified Causal Loop Diagram

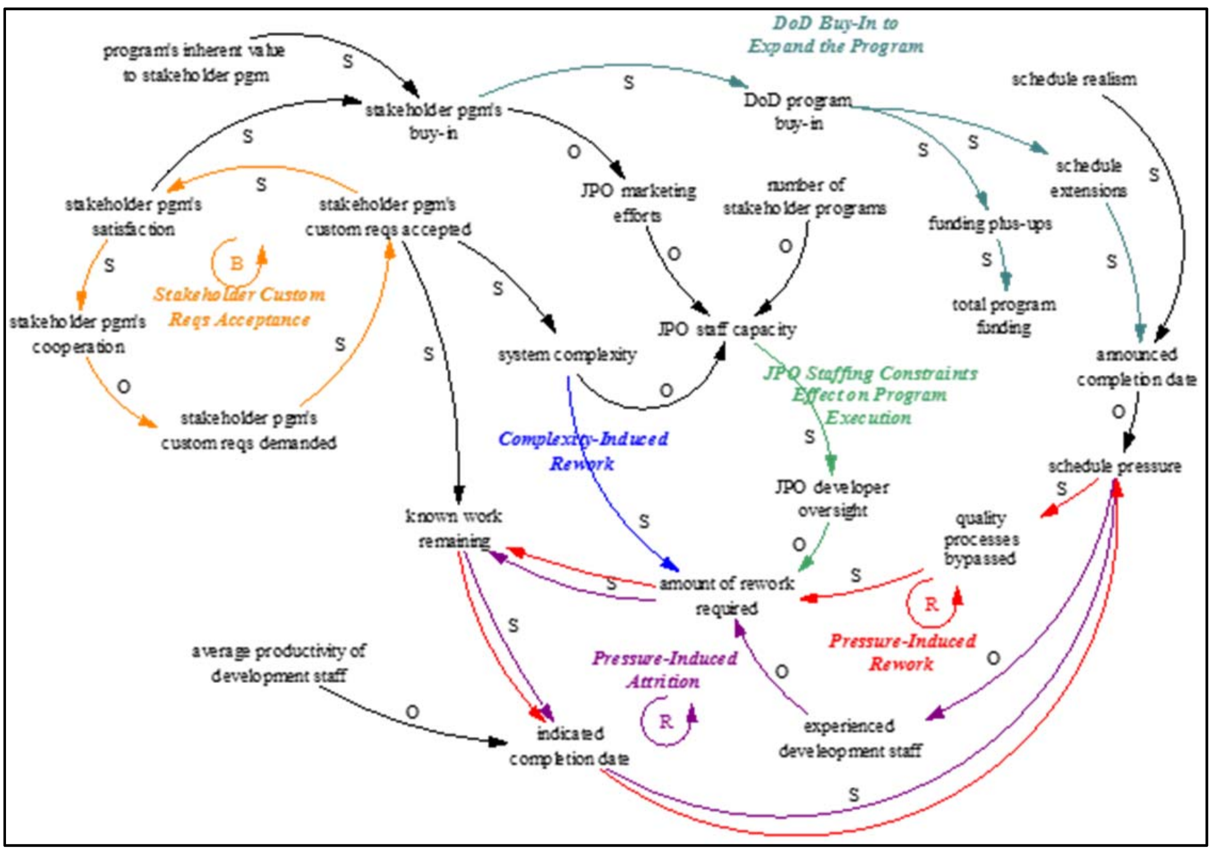

Figure 11. Causal Loop Diagram of the Joint Program

Acquisition Risks in a World of Joint Capabilities: A Study of Interdependency Complexity

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Abstract

This research examines DoD acquisition from the context of a network of interrelated programs that exchange and share resources for the purpose of establishing joint capabilities. The research focuses on the joint space of major defense acquisition programs (MDAPs): the space where transactions form interdependencies among MDAP programs. The research is especially salient because, to date, little is known about the risks associated with interdependent activities. This paper provides a short description of some of the network characteristics of the funding and data interdependencies of major defense acquisition programs. Where the discussion focused on descriptions, recent advances allow the ability to test the structural descriptions on program performance. In exponential random graph models (ERGM), the ties serve as predictors of performance. ERGMs are capable of testing a host of structural arrangements for their influence on outcomes. Employing Markov Chain Monte Carlo Maximum Likelihood Estimation techniques, probabilities can be ascertained. Over the coming months the structural nature of the interdependencies will be analyzed and evaluated for their influence on acquisition performance.

Introduction

In a world of insurgent and asymmetrical warfare, no defense organization is an island. While the Services have engaged in a host of coordinated efforts in the past, the need for situational awareness and rapid response rates demands the synergistic benefits that only wide-scale cross-integration and interoperability affords. Never in the history of the DoD has the rapid fielding of flexible and adaptive technology for countering unconventional and time-sensitive threats been more important.

This research examines DoD acquisition from the context of a network of interrelated programs that exchange and share resources for the purpose of establishing joint capabilities. The research focuses on the joint space of major defense acquisition programs (MDAPs): the space where transactions form interdependencies among MDAP programs. The research is especially salient because, to date, little is known about the risks associated with interdependent activities.

Unfortunately, by and large, the literature on interdependent activities is steeped in contradictory findings. For example, some argue that tight-knit arrangements are more likely to have the social traction needed to overcome environmental difficulties (Sosa, 2011), whereas others argue that loose coupling, or weak ties, may be a better solution (Granovetter, 1973). Some claim that more information is the key to benefit attainment (Comfort, 1994), whereas others claim that more information leads to a false sense of security (Hall, Ariss, & Todorov, 2007). Yet, despite the absence of consistent sage advice,

resource limitations and a demand for comprehensive solutions continue to push organizations toward complex structures for the delivery of products and services.

For this research, jointness, interdependency, exchange, and partnerships all refer to a similar concept: the notion that autonomous organizations build relationships to obtain resources to provide capabilities that, when looked at in totality, form network structures. While it is true that at the individual pair-wise level, these exchanges exist as explicit transactions for the transfer of data, labor, capital, or materials, it is also true that the totality of the various dimensions, coupled with the turbulence of perturbations, influences the cost, schedule, and performance of the acquisition effort.

Organizations in the past sought to limit interdependencies to maintain control over the environment. More recently, however, organizations have sought to leverage the benefits that interdependencies, or partnerships, can provide. Thus, discussions of the nature of structure and how to best organize in the face of increasing needs for holistic comprehensive solutions has taken center stage. The key question seems to be whether organizations can benefit from interdependence while minimizing the negative influences of environmental turbulence. The question, thus, becomes, what structural arrangements and behavioral practices are conducive to achieving the benefits of coordinated actions? The following research explores the nature of the funding and data interdependencies that characterize major defense acquisition programs.

Interdependent Networks

A novice's glance into the field of interdependent organizational-based networks is likely to reveal a terminological jungle of abstract and obscure vocabulary. This section of the report seeks to convey many of the more common network terms and place them in the context of DoD acquisition. Table 1 in the appendix provides a glossary of several of the key terms. At the onset, it is important to recognize that the term *social* is used in a specific empirical context for understanding programmatic interactions: "Social systems of interaction" form the basis from which material equipment and organizational capacities get things done (Turner, 1988).

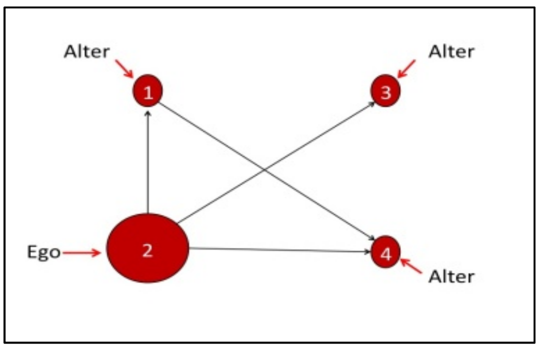
Wasserman and Faust (1994) defined the social network perspective as a focus on the relationships that exist among entities and the patterns and implications of these relationships. Overall, the vantage point is that

- actors and their actions are viewed as interdependent rather than independent, autonomous units;
- relational ties between actors are channels for the transfer of resources; and
- network models view the structural environment as providing opportunities for, or constraints on, individual and collective action (Wasserman & Faust, 1994, pp. 3–4).

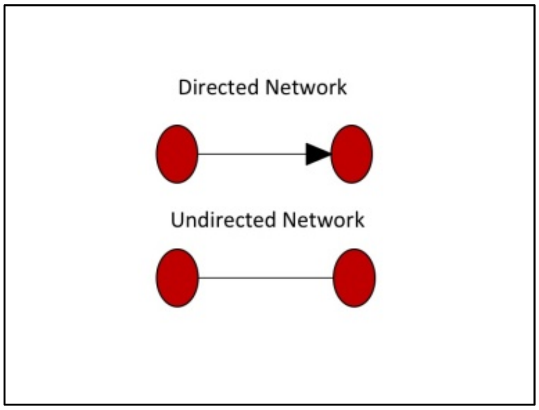
Organizations have long been viewed as resource exchanging agents. When considered in this light, each organization takes input and converts it into outputs that are then provided as inputs to another organization. Nonetheless, in the past, organizations often sought to maintain control over practices and procedures by restricting access to outside influences. Hierarchical organizational models were pursued because they provided stability. But the hierarchical approach was found to be ill-suited to situations in which needs and demands evolved. Hierarchical approaches, due to their inability to adapt, risked the obsolescence that occurred from the inability to adapt to changing needs.

Over the years, researchers have consistently found that demand uncertainty is a key contributor to the choice to forego hierarchical-based approaches in favor of organizational networks. Demand uncertainty arises when organizations lack the ability to predict near-future needs. When organizations are confronted with high levels of demand uncertainty, they require the flexibility to make rapid shifts in their service delivery and production cycles—shifts that a hierarchical approach cannot accommodate. Because networks offer an expanded set of options, they allow the ability to respond to a wider range of contingencies. For example, under asymmetric warfare conditions, the types of solutions that may be required are difficult to predict a priori. Given the uncertainty of the demands of the battle space, warriors require a wide arsenal of alternative and complementary approaches—approaches that must be accessible at a moment's notice. When demand uncertainty is low, organizations often choose more simplistic hierarchical approaches. Under high demand uncertainty, organizations require the ability to leverage a variety of capabilities irrespective of the boundaries of a given organization's purview (Jones, Hesterly, & Borgatti, 1997).

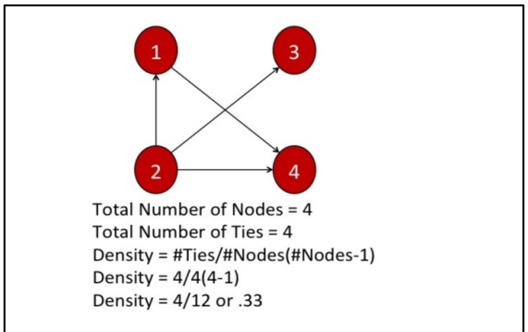
In the work setting, network actors (or nodes) often represent people, teams, or organizations. A tie represents some form of interaction or relationship. In short, network structures provide the "plumbing" for the flow of resources through the network. Interdependent networks are complicated by the fact that they are multidimensional, and as such, understanding their behavior requires consideration of multiple levels of analysis. Typically, networks can be characterized in light of four basic levels: the individual, the subnetwork(s), the entire network, or the multiplex network. A multiplex perspective considers the node from a multi-network consideration. For example, in this report, major defense acquisition program (MDAPs) are examined in light of the performance of the individual program as well as its resulting performance in two different networks: (1) a data-sharing network and (2) a shared budget network. Cross-level effects occur when behaviors at one network level influence behaviors at another network. Cross-level analysis involves looking at behavior across the various networks. The failure to consider cross-level effects may result in misinterpreting the full set of consequences that occur from network behaviors.

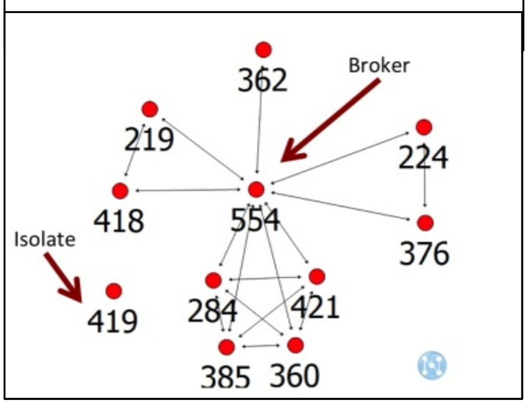


At the individual (or node) level, an ego is the central node of interest, and those connected to the ego are known as alters (see Figure 2 in the appendix). A network rendering from the context of an ego is referred to as an ego-network. A dyad consists of an ego and its adjacent alter. As discussed further in the next section, examining data in light of the dyads (or pairs) provides the ability to test the influence that one node has on another.



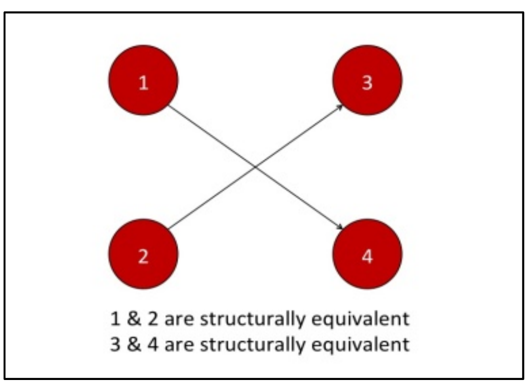
A directed network is one where the flow of resources moves in a specific direction, either inbound to an ego or outbound from an ego (see Figure 3 in the appendix). For example, the data-sharing network identified previously is a directed network because the data flow from one program to another. A directed network can be either sequential or reciprocal in nature. Alternatively, an undirected network is one that is "pooled." In other words, the nodes share a common connection (i.e., a budget), but there is no directional component to the tie. In this case, the tie indicates that the two programs share a common budget.





A node is labeled as a broker when it connects two distinct subnetworks. So in Figure 4 in the appendix, Program Number 554 Multifunctional Information Distribution System Joint Tactical Radio System (MIDS JTRS) acts as a broker between three subnetworks. An isolate is a node with no ties. Again, in Figure 4 in the appendix, Program Number 419 (EA 6B Prowler) is an isolate. In directed networks, a node can serve as a transmitter, a receiver, or a carrier. A bridge is identified when a tie spans two subnetworks. Structural equivalence occurs when two nodes are structurally similar (see Figure 5 in the appendix).

Relying on matrix algebra, a number of metrics have been devised throughout the years to measure networks. Some of the metrics occur at the node or ego level, and others are at the subnetwork or whole-network levels. Nodes are often considered in light of their position, or role, in the network. Many of the ego-level metrics are calculated relative to others in the network.



The degree of a node is the number of ties that a node exhibits. These ties can be measured as inbound or outbound (or both) in a directed network. Another measure is the geodesic distance that one node may be from another. Adjacency identifies direct connections while reachability identifies whether any two nodes are capable of connecting by way of other nodes. Degree centrality identifies the number of ties that a node possesses. The more ties relative to others, the greater the centrality. Closeness, on the other hand, indicates how close a given node is to the remaining nodes. When all of the nodes are close to all of the other nodes, the interaction level among the nodes is typically high.

Network size is often calculated as the sum of the number of nodes or number of ties (see Figure 6 in the appendix). Sometimes networks (or subnetworks) are measured by their longest, or shortest, path. The bridge identified previously is often of interest because it indicates that if the tie between the two nodes can be cut, the network can be disconnected or reduced to its subnetworks. The same holds true for the broker. If a broker is eliminated, the network will be reduced to a number of subnetworks. Node connectivity identifies the minimum number of nodes that have to be removed to disconnect the network. Betweenness is the extent to which a given node lies between other nodes and, thus, could act to facilitate or block the flow of resources.

Density refers to the proportion of ties relative to the absolute total. Relational embeddedness refers to the quality and depth of a single dyadic tie. Structural embeddedness refers to the extent to which a node's alters are connected to each other. Because structural embeddedness reflects the degree of the interactions, it is often used as a proxy for understanding network actions.

In the study of networks, scholars often take either a structural or a connectionist approach. Structural approaches examine the structure of the network and its influence on key variables of interest. Connectionists, on the other hand, focus on the flows between the nodes. Those who study social capital tend to focus on the possibilities of actions that social ties provide. Others, however, tend to be more concerned with diffusion and the dynamics of network change over time. Still, other studies focus on why and how networks develop, how and why they change over time, and finally, what influences they exert. Social capital is mostly studied at the individual level, and diffusion is observed from the perspective of the entire network.

Studies of the influence of dyadic ties on performance have mixed and contradictory findings. For example, Perry-Smith and Shalley (2003) found that weak ties led to creativity, but others claim that strong ties are more advantageous (Sosa, 2011). Others claim that it is not the number of ties but rather the depth of the engagement that matters. No one would be surprised by the idea that relative to fewer ties, more ties may provide organizations with better information that might promote enhanced decision-making. At the same time, information overload and difficulties with scrubbing data to provide information at the proper specification level have become real problems for many managers.

Similarly, studies of embeddedness are equally contradictory. According to some, the more each node knows about the others, the more constraints there are on each other's behaviors. This is often seen as a positive. Parties gather information on whom to avoid as well as potential opportunities and synergies. Structural embeddedness allows the use of sanctions since knowledge of misfeasance influences reputational value. But these constraints can backfire and actually restrict flexibility. Too much embeddedness can also create problems. It can lead to feuding, group think, and welfare support of weak members. Social aspects such as restricting access to exchanges, imposing collective sanctions, and making use of social memory and cultural processes all influence nodal behavior. Apparently, networks and ties matter, but the extent of the influence is highly debatable.

Much of the incongruity in the findings may be due to the difficulties associated with measurement and data collection. Researchers are challenged by the burden of the data collection requirements, and organizations are often frustrated by the extent of the data request. Because multilevel data are needed for each specific relationship, the data collection task can be onerous. Moreover, given that the study of networks is a fairly new phenomenon, typical organizational records often lack insights at a network level. When multilevel data are obtained, an analysis of variance statistical technique termed *hierarchical*

linear modeling or *multilevel modeling* is often employed because it allows the examination of multiple units of analysis simultaneously.

Despite these contradictory findings and data collection difficulties, the examination of networks and ties that manifest as interdependencies is likely to provide substantial insights into a number of issues. First, when considering cost and affordability, examining a program in isolation of the entire value chain is likely to provide erroneous information. Second, a wealth of research illustrates the importance of risk management. Considering the risks of a given program without considering its interdependencies may underestimate the true risk level. Next, in the decision of a start-up or termination, it is essential to know how the inclusion or removal of a program will influence its n-order neighbors. Finally, network conditions may exert powerful influences over program sustainability. The following discussion explores the funding and data networks employed in the acquisition arena.

Interdependency Descriptions

Two sets of interdependencies are examined below. One set reflects funding interdependencies and the other captures data interdependencies. In the organizational arena, interdependencies can be viewed in three ways. As Thompson (1967) illustrates, network arrangements can be pooled, sequential, or reciprocal. Under a pooled arrangement, network actors draw down from a common pool of resources. Under this scenario, the actors do not interrelate, but they are nonetheless interdependent because they all share a common resource that can be depleted. The funding interdependencies described in the next paragraph reflect a pooled relationship. These acquisition programs share a common program element. Thus the interconnections reflect their interdependencies on a common funding source. Sequential relationships are often termed supply chains. In these scenarios resources flow in a sequential manner from program to program. Reciprocal relationships are often seen as the most complex and have the greatest risk. In this case, resources are exchanged and, as a consequence, there is a two-way link among the programs.

Figure 1 in the appendix displays the funding interdependencies over time. As displayed in the figure, the interdependencies have grown increasing complex over time. The density has grown from a low of 6% to a high of 22%. Figure 2 in the appendix reflects the polynomial regression equation and its associated bivariate plot showing growth over the six-year period. Figure 3 in the appendix illustrates the data interdependencies. As demonstrated in the diagram, these interdependencies reflect 326 ties and range from 27% inbound to 16% outbound.

Figures 4 and 5 in the appendix illustrate that both the data and funding interdependencies reflect “preferential attachment.” Preferential attachment was popularized by Barabasi and has gained tremendous attention over the past 10 years. Preferential attachment (or more commonly a hub-and-spoke model) is the tendency for nodes to establish relationships (or links) with nodes that have a high number of connections with other nodes. As a result, the connections demonstrate a power law distribution. The power law distribution is important because it illustrates that the network can be destroyed by eliminating the “hubs.”

Figures 6 and 7 in the appendix show the funding and data interdependencies by Service and FCB. As shown, the Navy appears to illustrate the greatest number of funding and data interdependencies. Interdependencies by FCB appear fairly mixed.

Future Activities

This paper provides a short description of some of the network characteristics of the funding and data interdependencies of major defense acquisition programs. Where the discussion focused on descriptions, recent advances allow the ability to test the structural descriptions on program performance. In exponential random graph models (ERGM), the ties serve as predictors of performance. ERGMs are capable of testing a host of structural arrangements for their influence on outcomes. Employing Markov Chain Monte Carlo Maximum Likelihood Estimation techniques, probabilities can be ascertained. Over the coming months, the structural nature of the interdependencies will be analyzed and evaluated for their influence on acquisition performance.

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Acknowledgements

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Appendix

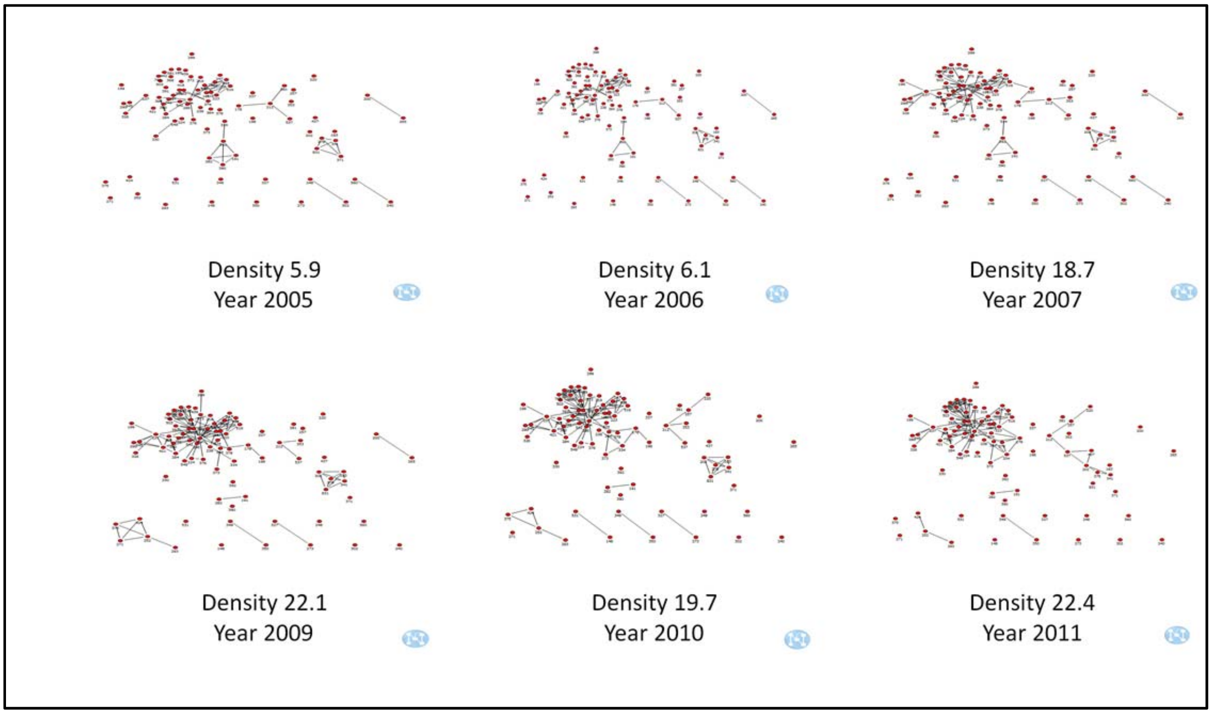

Figure 1. Funding Interdependencies

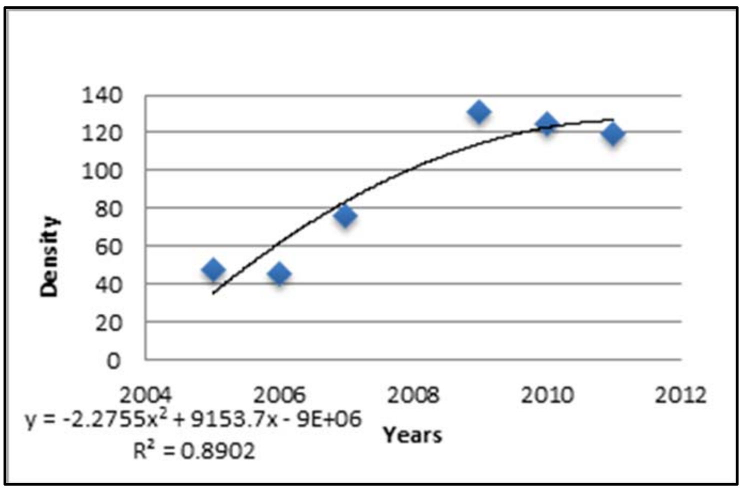

Figure 2. Funding Density Over Time

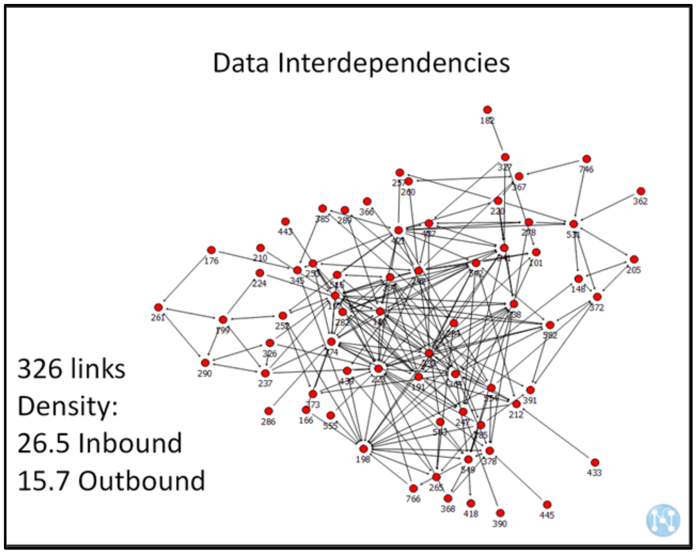

Figure 3. Data Interdependencies

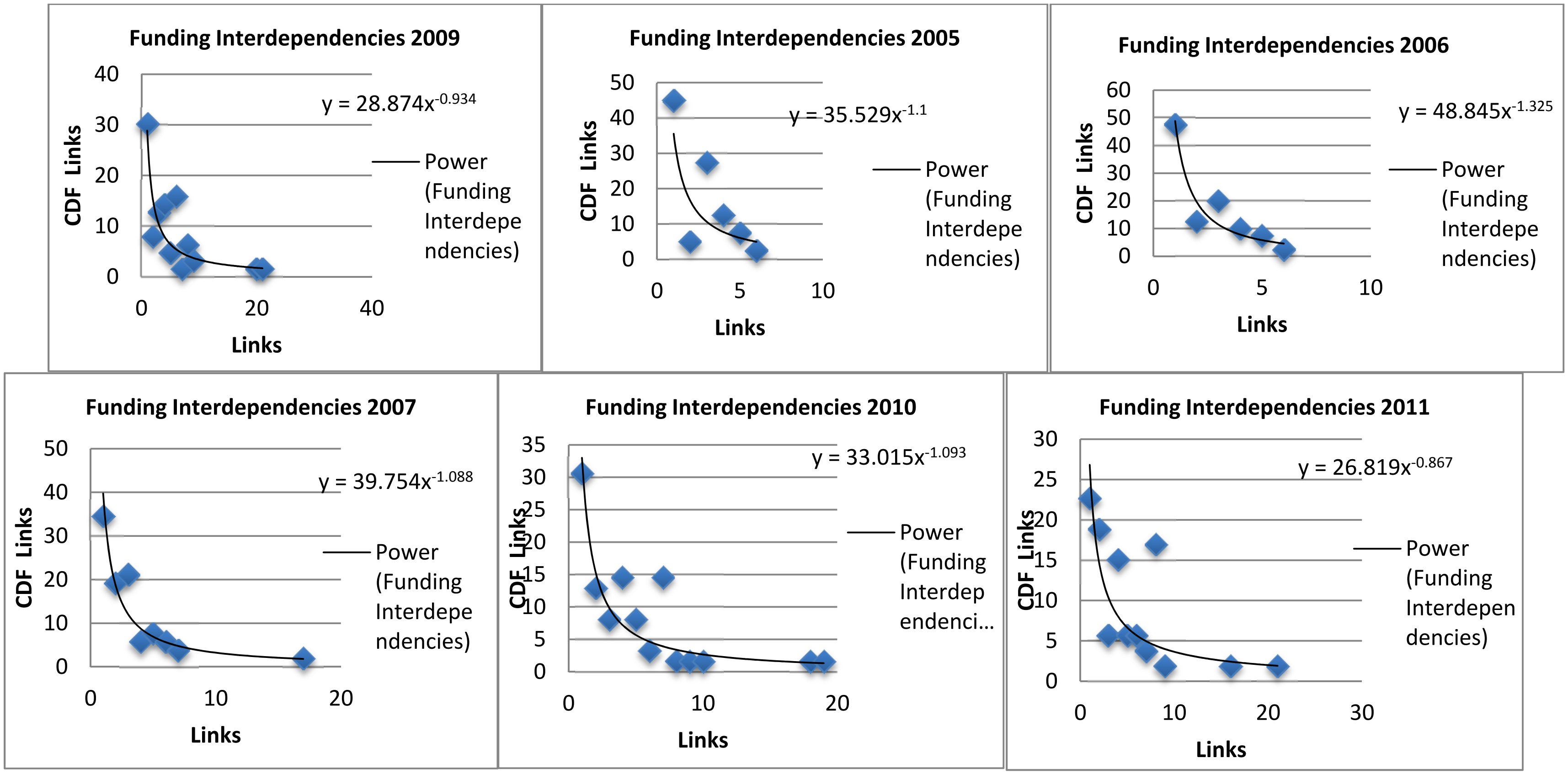

Figure 4. Preferential Attachment of Funding Interdependencies

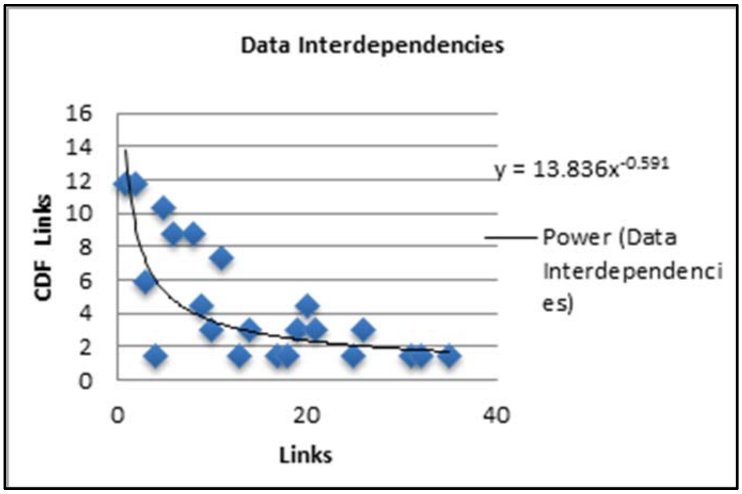

Figure 5. Preferential Attachment of Data Interdependencies

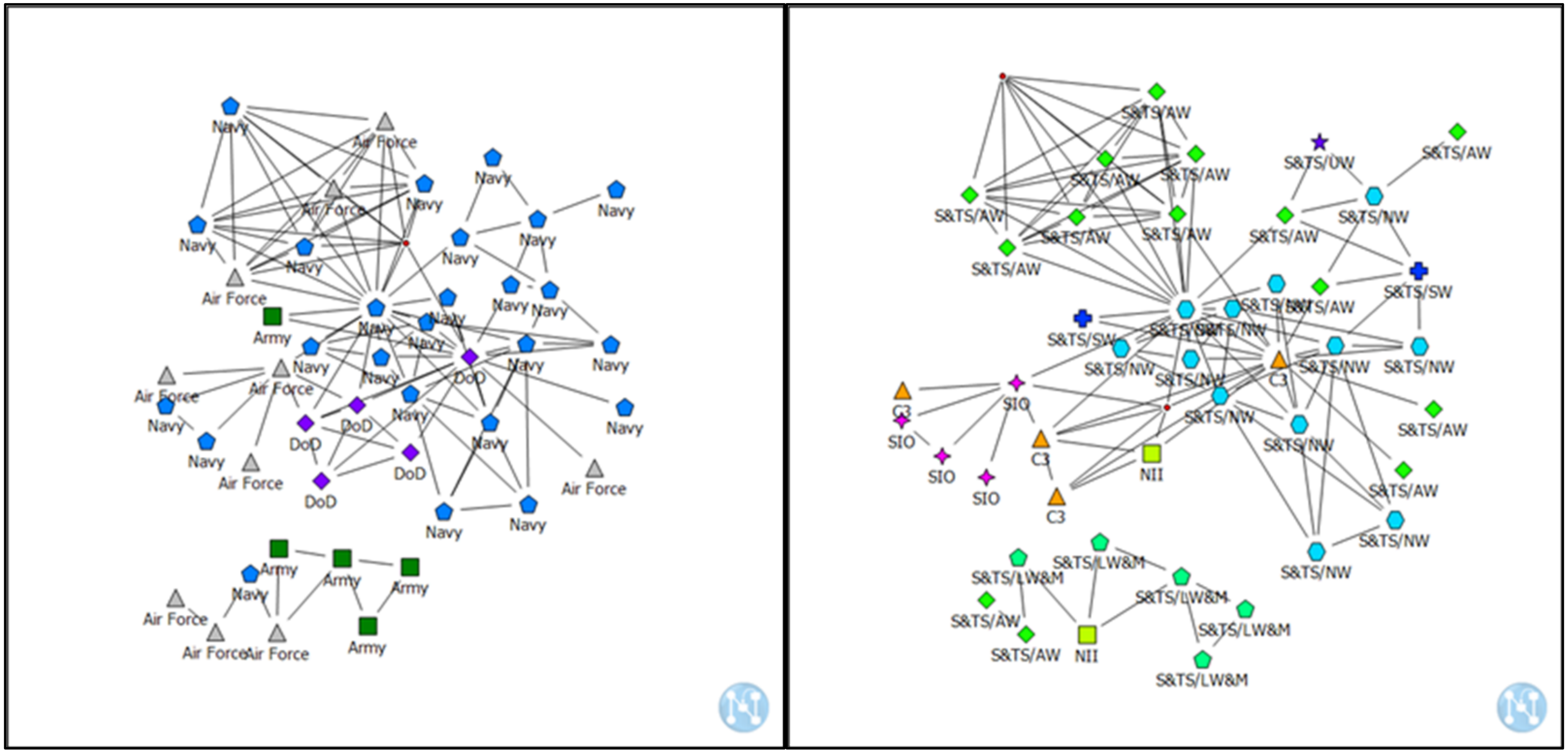

Figure 6. Funding Interdependencies by Service and FCB

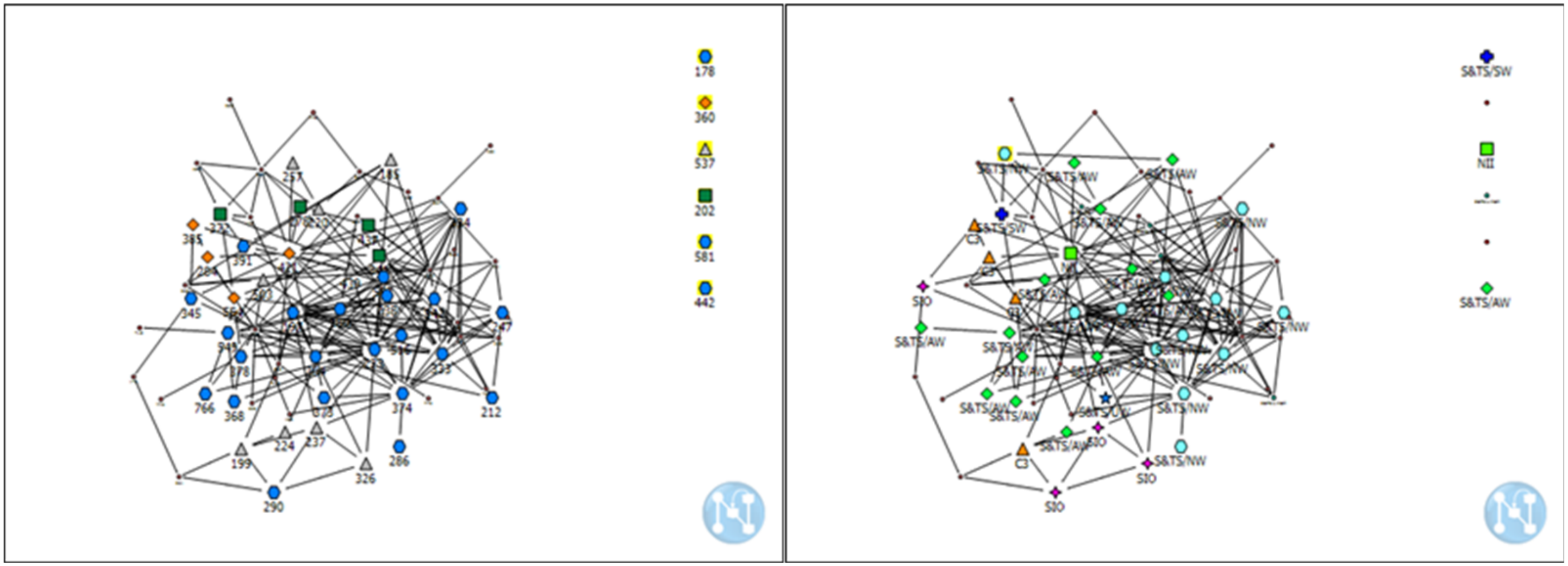

Figure 7. Data Interdependencies by Service and FCB

Table 1. Common Network Teams

Node: a person, team, organization, computer, etc., in a network
Tie: a connection between two nodes
Directed Network: a network where the tie is directional in nature
Undirected Network: a network where the ties are not directional
Ego: the subject of the discourse
Alter: the node that the ego has ties with
Ego Network: the network in light of a given ego
Dyad: two nodes linked into a pair. Networks can be decomposed into their dyads, or pairs.
Structuralist Paradigm: sees the network structure as the defining characteristic of an individual node's behavior. By extension, two nodes that share structurally similar characteristics will witness similar outcomes.
Connectionist Paradigm: The focus is on the resources that flow through the ties; the ties act as conduits for the flow of resources.
Diffusion: a measure of the spread of an innovation or characteristic throughout the network
Social Capital: The primary focus of the Connectionist paradigm is concerned with the resources that are gained (or lost) via the ties, and it views success as a function of these ties.
Structural Capital: The primary focus of the Structuralist paradigm is concerned with the position of nodes in a network and how this influences outcomes.
Centrality: the extent to which a given node(s) dominates the number of ties. When only a few nodes have a large number of ties compared to the others, the network is viewed as highly centralized.
Structural Equivalence: Actors (or nodes) are structurally equivalent to the extent that they are similar in their ties.
Relational Embeddedness: relates to the quality and depth of a single dyadic tie
Structural Embeddedness: relates to the extent to which a given node's alters are interconnected
Geodesic Distance: represents how far one node is from another. It is often represented as how near or far a node is from another.
Closure: Is a measure of the number of triads (or connections among three nodes) that exist in the network
Structural Hole: A hole in the network that a node could bridge and thus act as a go-between. In this way, structural holes can often control the two nodes that they connect.
Broker: Per the definition of *structural hole*, a broker spans two or more subnetworks.
Multiplex Ties: when a given node connects with another node in multiple networks. For example, a node may be connected to another node in both a funding network and a data-sharing network.

Homophily/Heterophily: indicates the extent to which one node is similar to another on key characteristics
Degree Distribution: the variance in the distribution of ties in a network
Network Connectivity: reflects the "size" of the network by the longest path from one node to another
Network Density: the proportion of ties in a network relative to the total number possible
Pattern of Clustering: refers to the absence or presence of subnetworks
Degree Assortativity: reflects the degree to which nodes with a similar number of ties connect with each other
Cohesion: the degree to which nodes are connected directly to each other. Under low cohesion, a number of cliques (or subnetworks) will be observed.
Bridge: a tie that is critical to the connectivity of the network. Elimination of the bridge is likely to result in a large number of factions.
Path Length: the length from one node to another. Typically measured in terms of how many nodes are in between the two.

Leveraging Structural Characteristics of Interdependent Networks to Model Non-Linear Cascading Risks

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Abstract

This paper describes our continuing efforts to forge new ground in identifying the effects of interdependency on acquisition and, if needed, uncovering early indicators of interdependency risk so that appropriate governance oversight methods can then be isolated. Specifically, we seek to study the topologies of Major Defense Acquisition Programs (MDAPs) networks and associated cascading consequences of interdependencies in such highly dependent networks. Since the start of this new project phase a couple of months ago, we have begun harnessing the extensive data that has been collected over the years in the form of Defense Acquisition Execution Summary (DAES) documents for the MDAPs. We present a road map of our research plan and our preliminary results in our ongoing efforts on leveraging network structure and automatic data extraction to study cascading risks. We will also identify the challenges to data acquisition.

Introduction

This research seeks to study the structures of the Major Defense Acquisition Programs (MDAPs) networks and the associated cascading consequences of interdependencies in such highly dependent networks. It involves identifying the effects of interdependency on the acquisition process and, if needed, uncovering early indicators of interdependency risk so appropriate governance oversight methods can then be isolated. Hence, this research seeks to address the problem that there is little insight on the effects of interdependencies and a lack of tested metrics to provide early indication of the acquisition risks of interdependent programs. It breaks ground in the area of (i) studying non-linear cascading effects in the context of a network of MDAPs consisting of some not-so-

successful programs (that which experiences cost growth) as compared to (ii) the study of the decision mechanisms of successful programs. Lessons learned from this comparative analysis would help model the behavior of other MDAP programs. The project will use the extensive data that we have collected over the years in the form of Defense Acquisition Execution Summary (DAES) documents for the MDAPs.

This work builds on our previous results (Raja, Hasan, & Brown, 2012) obtained from a manual analysis of data belonging to a small network of MDAPs representing a case study. Our goal was to model "what-if" analyses that would help decision-makers to gain insight on the cascading effects of perturbations among interdependent networks and take appropriate measures to handle them. We used the case study to first determine whether the data required to build a decision-theoretic model is available and then study whether this decision-theoretic model captures the cascading interdependencies that are of interest to us. We also examined the data investigation process to identify the challenges that were encountered. Our results showed that MDAP-related data characteristics support the multiple perspective study of perturbations and it is possible to recast the study of cascading effects as a sequential decision problem. We identified local and non-local issues that when left unmitigated led to performance breaches in the MDAPs. We also observed that it is crucial to consider the uncertainty in action outcomes in the decision-making process and that a non-local perspective may help explain a performance breach in situations where a solely local perspective does not. These observations supported our conjecture that a decision-theoretic model is a good methodology to study interdependencies in the MDAP network and to capture early indicators of interdependency risk. Finally, we captured the informational value in the existing data and the challenges inherent in the data collection process with respect to their role in isolating risks and initiating appropriate government oversight methods.

The sheer volume and complexity of the data required to populate our decision-theoretic models effectively has led us to identify methods for *automating* the data extraction, network analysis, and construction of the decision model that is the focus of our current work. This project, initiated a couple of months ago, has the following research goals: (1) Examine and compare the network structure characteristics of interdependent regions belonging to successful and not-so-successful MDAP programs to augment our current work in "what-if" analyses. (2) Automate the data extraction and analysis process by leveraging algorithms for decision support as well as image and text analysis. (3) Continue to identify the challenges in acquiring the data from the government and program managers. In this paper, we will discuss our proposed ideas for this year-long project and the initial work we have done to achieve the above mentioned research goals.

Background

It has been shown that data are the foundation for decision-making in the acquisition environment. The Department of Defense (DoD) has spent a significant amount of effort working across the organization to identify useful sources of data and to conduct analyses. The importance to acquisition research of studying MDAP interdependencies was emphasized during the 2012 Annual Acquisition Research Symposium by the introduction of a new panel titled Predicting Performance and Interdependencies in Complex Systems Development. Prior research has established that MDAPs are demonstrably interdependent and that they can be thought of as networks of interdependent programs (Flowe, Brown, & Hardin, 2009; Flowe, Kasunic, & Brown, 2010; Lewin, 1999). Also, the acquisition paradigm established in statute (10 U.S.C. 2434; Defense Acquisition Workforce Act, 1990), in policy (DoD 5000.02; Under Secretary of Defense for Acquisition, Technology, and Logistics [USD(AT&L)], 2008), and in regulation tends to favor the notion of MDAPs as being

independent, which would cause exogenous factors caused by interdependence to be overlooked or misinterpreted.

Although it is critically important to understand the program interfaces and interdependencies, there are few tested and proven tools for program managers and acquisition executives to probe the joint space or to track the cascading effects that the joint space might trigger. There is reason to believe that the exogenous issues generated from the shared domains remain unnoticed to the extent of causing the program to potentially experience severe performance degradation (Brown, 2011). The complexity of the joint environment is likely to have a direct bearing on acquisition activities. The precise effect on acquisition, and its resulting managerial implications, are, as of yet, unknown. We believe that given the frequency with which government agencies are moving toward joint initiatives, the findings of this research project based on DoD programs may prove instrumental to a wide-ranging audience.

Furthermore, at the 2012 Acquisition Symposium, Dr. Frank Kendall III, the Under Secretary of Defense for Acquisition, Technology, and Logistics (USD[AT&L]), discussed the DoD's strategic priorities, especially around acquisition. These priorities included achieving affordable programs that execute well and improving efficiency (via Better Buying Power and other initiatives). We believe the work described in this paper will help us understand the performance of the programs in various scenarios and contribute directly to the above priorities by achieving affordable programs that are successful as well as improving overall efficiency.

Along with other researchers (Brown & Owen, 2012), we have begun to harness a network-centric approach to study DoD acquisition and focus on an MDAP network of interrelated programs that exchange and share resources for the purpose of establishing joint capabilities. Some work (Zhao, Gallup, & MacKinnon, 2012) has been done to analyze the unstructured and unformatted acquisition program data using a data-driven automation system called lexical link analysis (LLA). LLA is used to determine the correlation between system interdependency and development costs in an effort to enable acquisition researchers and decision-makers to recognize important connections that form patterns derived from dynamic data collection. In other work (Han, Fang, & DeLaurentis, 2012), a Bayesian Network (BN) method is used to assess the cascading effects of requirement and systems interdependencies on risk in an effort to effectively analyze alternatives in a capability-based acquisition strategy. The technique is evaluated within a synthetic network and identifies critical systems and requirements.

We believe our work will help us understand the performance programs in various scenarios and contribute directly to the above priorities by achieving affordable programs that are successful as well as improving overall efficiency.

Research Methodology

The overall goal of this research is to continue our efforts to forge new ground on identifying the effects of interdependency on acquisition and, if needed, uncovering early indicators of interdependency risk so appropriate governance oversight methods can then be isolated. Hence, this research seeks to address the problem that there is little insight on the effects of interdependencies and a lack of tested metrics to provide early indication of the acquisition risks of interdependent programs. It breaks ground in the area of (i) studying non-linear cascading effects in the context of a network of MDAPs consisting of some not-so-successful programs (that which experiences cost growth) as compared to (ii) the study of the decision mechanisms of successful programs.

The information pertaining to acquisition research is overwhelming and multifarious. It appears to be a daunting task for the acquisition researchers, let alone the program managers, to integrate and understand the vast and dynamic data in a coherent way. To define the interrelationship among the MDAPs from a network-centric viewpoint and to identify different network dependencies within the domain of MDAPs, the following set of data resources are useful:

- Monthly DAES reports that provide an early-warning report on the status of some program features such as cost, schedule, performance, funding, etc.
- SARs that summarize the latest estimates of cost, schedule, and technical status to be reported annually in conjunction with the President's budget
- Program Element (PE) documents (called PE docs or R-docs) that are used to justify congressional budgeting process
- Program Objective Memoranda (POMs) which are submitted by the components (military departments and DoD agencies) to OSD comptroller

Next we describe the main tenets of the four research tasks illustrated in Figure 1. Since we are in the very early stages of this project, we will describe our proposed research for each of the tasks and also discuss initial progress we have made so far.

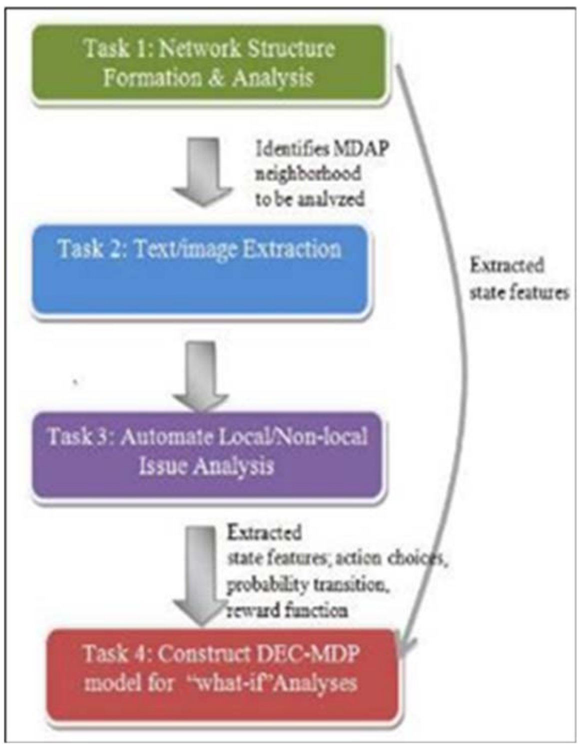


Figure 1. Research Goals

Task 1: Network Structure Formation and Analysis

We plan to address the following two questions as part of this task:

- What are the essential features of the network that reveal the joint space dynamics?
- What are the relative priorities associated with these features and how do they affect the network relationship?

Network Structure Formation. From our previous study, we identified both successful and not-so-successful programs with respect to performance breaches. For the current study, we plan to build funding networks for these two types of MDAPs. We will study the Program Element (PE) accounts of these programs from their "Track to Budget" files and would find their first-order funding neighbors. This process would enable us to define the network topology for the analysis of its properties.

Network Structure Analysis. Network theory (Ahuja, Magnanti, & Orlin, 1993; Albert, Jeong, & Barabási, 2000) provides useful tools to calculate and understand quantities or measures that capture significant features of the network topology. These measures help analyze the network data based on the structure of the network and also help to understand how those properties are related to the practical issues that we care about. In other words, network theory provides a rich set of measures and metrics that can help understand what the network data may tell. A key metric for network data analysis is various types of centrality measures. Centrality quantifies how important are the nodes (or edges) in a networked system. There are a wide variety of mathematical measures of node centrality (Bonacich, 1987; Borgatti, 2005; Freeman, Borgatti, & White, 1991) that focus on different concepts and definitions of what it means to be central in a network. A simple but very useful example is the measure called degree. The degree of a node in a network is the number of edges attached to it.

In case of an MDAP funding network, degree-centrality would show how many funding neighbors a particular MDAP has and how it could be related to the performance of the program. For example, having many funding partners incurs more risk in terms of being affected by the cascading consequences. Many of the standard algorithms for the study of networks are already available, ready-made, in the form of professional network analysis software packages. Some of the software packages for analysis of network data are Paejk (http://vlado.fmf.uni-lj.si/pub/networks/Pajek/), Netminer (http://www.netminer.com/index.php), yEd (http://www.yworks.com/en/products_yed_about.html), JUNG (http://jung.sourceforge.net/), and so forth.

State of the program in our decision-theoretic DEC-MDP model captures the critical information at a specific point in time that will support the decision-making to guarantee good performance. To describe the state space and to identify some of the key state features, we will employ an appropriate network analysis tool for the MDAP networks. We plan to address the following question: What are the network properties that essentially contribute towards the good/poor performance of the respective MDAPs? Our goal is to measure some of the important centrality measures for the network and correlate it with the performance of the node (the program). Centrality measures help us to determine (i) which nodes are important in the network and (ii) to assess their importance with respect to their performance.

We plan to first define an undirected funding network for a chosen MDAP. We will then measure the following network centralities for 5/10 years time span for all MDAPs: degree, betweenness, closeness, similarity, local clustering coefficient, and so forth. We discuss these metrics in greater detail in the following paragraphs. We also plan to calculate the performance factor for 5/10 years time span for all MDAPs, based on a composite metric (it may include the breach factors, %PAUC, funding delta, and so forth from SAR files). This will help us to determine how each of the centrality measures affects the performance of the programs over time.

The above methodology will enable us to identify additional state features to describe the state space of the program within the DEC-MDP model. The following is the list of features of interest:

- Feature 1: Program ID
- Feature 2: Current Year
- Feature 3: Current Month
- Feature 4: Cost (APB) Status—for nine months, starting from the current month
- Feature 5: Cost (Contract) Status—for nine months, starting from the current month
- Feature 6: Schedule (APB) Status—for nine months, starting from the current month
- Feature 7: Schedule (Contract) Status—for nine months, starting from the current month
- Feature 8: Performance (APB) Status—for nine months, starting from the current month
- Feature 9: Performance (Contract) Status—for nine months, starting from the current month
- Feature 10: Funding (APB) Status—for nine months, starting from the current month
- Feature 11: Funding (Contract) Status—for nine months, starting from the current month
- Feature 12: Degree Centrality
- Feature 13: Closeness Centrality
- Feature 14: Betweenness Centrality
- Feature 15: Local Clustering Coefficient
- Feature 16: Commodity Type
- Feature 17: Partner Abandonment

We have identified Feature 1 through Feature 11 to be useful features based on our past work. As part of this project, we propose to continue studying these features and introduce more network-centric features in the context of studying the role of interdependencies on performance. Features 12–17 capture some of the key network-centric features for the MDAP of interest. For example, Feature 12 (degree centrality) measures the connectivity of a program with other programs. A higher connectivity might incur higher risk because of its sharing of funding with many partners. Feature 13 (closeness centrality) measures the mean distance of a program from other programs. These centrality measures could offer better understanding about the propagation speed of the cascading effects. Feature 14 (betweenness centrality) measures the importance of the program that may reside in the overlapping region of more than one sub-network and which is able to control the flow of influence among different sub-networks. Feature 15 (local clustering coefficient) measures the formation of groups among the member nodes and it

may be related to the degree distribution of the network. For example, typically nodes with higher degree have a lower local clustering coefficient on average. Therefore, a node with a higher local clustering coefficient (and lower degree distribution) is most likely prone to lower risk. It is also useful to identify the “structural holes” in a network. If two neighbors of a node are not themselves neighbors, then we say that there is a “structural hole” existing among them. Identification of “structural holes” could be useful to analyze the propagation of cascading risks. As part of this task, we will study the usefulness of these features and also identify other new ones.

Initial Results on Task 1: Network Structure Formation

We define a funding network of an MDAP using the PEs that funded the MDAP’s RDT&E efforts. PE is the code number assigned by the comptroller. Since PEs fund multiple MDAPs, programs that share a common PE monitor could be isolated. Procurement PEs were not considered for defining funding networks since the RDT&E interdependencies were the most critical to program performance. The funding network and the associated R-docs allowed us to do a detailed study of the performance of the member nodes and to understand the cascading effects the funding network of the three MDAPs named MDAP_A, MDAP_B and MDAP_C. The original names of these MDAPs have been removed to retain the confidentiality of the programs.

Examination of the DAES reports and R-docs from the years 2006–2011 related to these MDAPs shows that MDAP_A and MDAP_B experience frequent performance breaches while MDAP_C appears to be performing as expected. We have built an evolving funding network of these three MDAPs based on the common PE accounts that they share with other MDAPs, such as MDAP_D-I. The relationship between the PE accounts and the MDAPs, extracted from the PE docs, is represented as bipartite networks. Figure 2 shows how the funding relationship of these three MDAPs and their neighbors change from 2006 to 2011. Since the PE docs for the year 2008 were unavailable, we couldn’t show the funding network for that year.

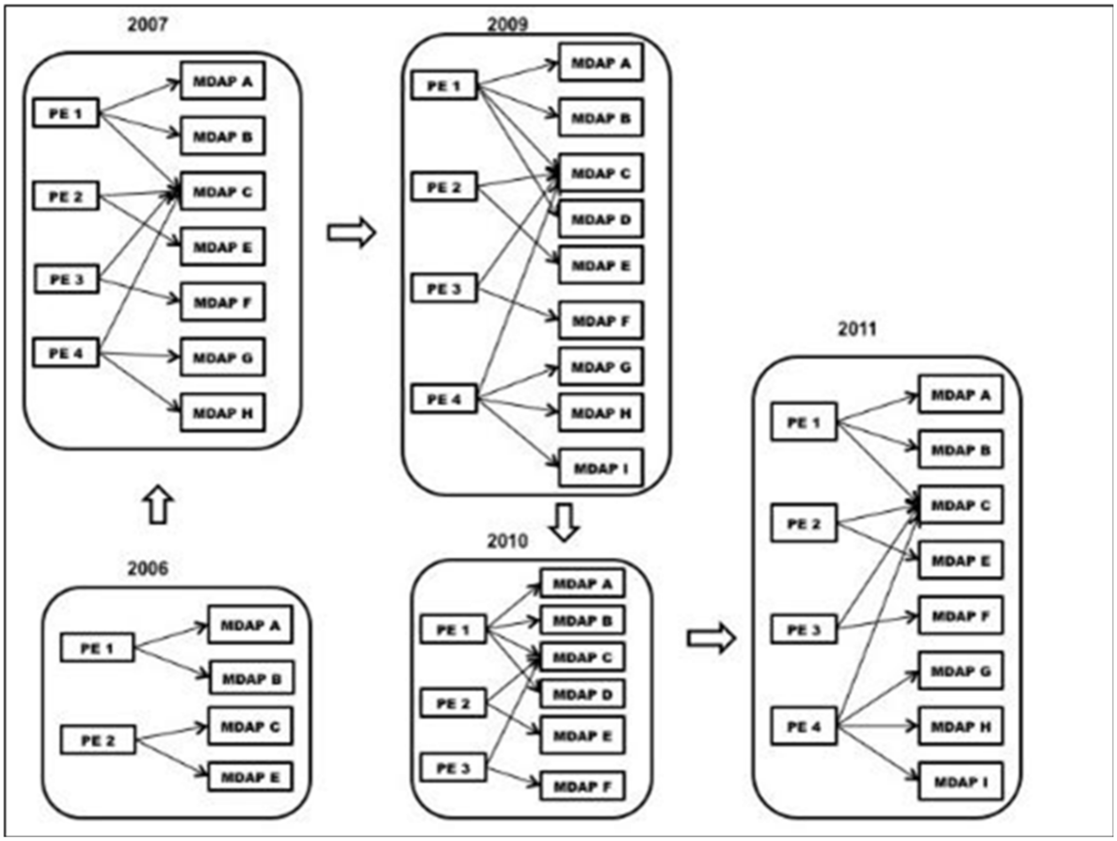


Figure 2. Evolving Funding Network of MDAP_A, MDAP_B, and MDAP_C

From these bipartite networks, we notice that MDAP_A and MDAP_B share only one PE account (PE 1), while MDAP_C shares multiple PE accounts (PE 1–4). It indicates that MDAP_C is prone to more inter-dependency risks.

Next we plan to measure the weight of the links between the PE account and the respective MDAPs based on the funding distribution as captured in the PE docs. This measurement can be obtained by comparing the POM and SARS data. The former describes what the PM says the program requires and the latter is what the program actually got. This comparison will give us a better understanding of the dependency of MDAPs on the associated PEs and the effect of expected and actual budget allocations on performance breaches. We will use these link weights as state features for the respective programs.

Task 2: Automated Data Extraction and Text Analysis

We plan to address the following two questions as part of this task:

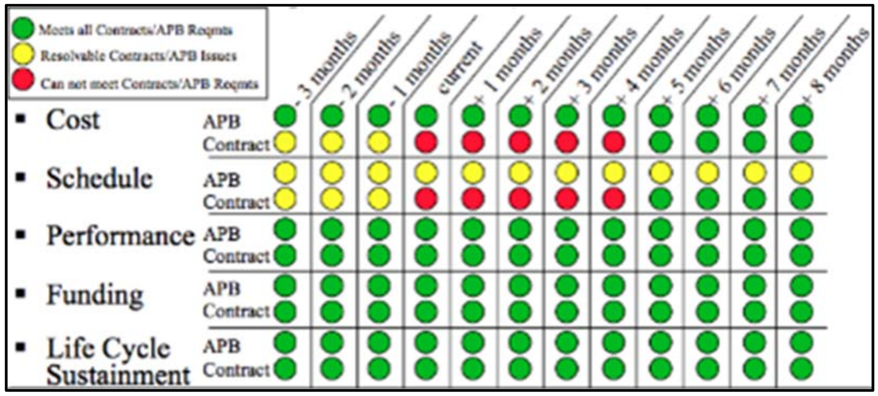
- What are the local issues that lead toward breach or near-breach situations?
- How often and why do the local mitigation efforts fail to improve the performance?
- How do we identify the non-local issues that result from the interdependencies?
- How do we determine the cascading effect through the network?

We plan to approach Task 2 from two perspectives: *Local perspective* where the analyses are based solely on the individual program's own data; and *Non-Local perspective*

where the analyses are based on the data of MDAPs existing in the joint space of the individual program. Lessons learned from these analyses should enable the stakeholders to take appropriate measures to improve the performance of the programs. Our objective in this task is to narrow down the wealth of data present in the DAES reports in order to capture useful knowledge about the status of individual MDAPs and the MDAPs in their network. This will be achieved as follows:

Automatic Data Extraction. The aim of this subtask is to bring the content of DAES reports, currently as Microsoft PowerPoint files, Adobe Acrobat PDF files, and Word documents, into a form suitable to further analysis. We will mainly focus on the *program status* and *issue summary*. First, bottom-up (pixel to block) image segmentation will be used in order to extract the layout of the document (O'Gorman, 1993; O'Gorman & Kasturi, 1997; Salleb & Hocini, 1996). It appears from the DAES reports that the part that requires further extraction is the *program status matrix* for the following items: Cost, Schedule, Performance, and Funding. The status of each of these items is given for *APB* and *Contract*. The status is a colored circle indicating three possible states: meet all contracts (green); resolvable contracts (yellow), and cannot meet all contracts (red). The status is given for the current month, past three months, along with a forecast for the upcoming nine months.

Once we extract the different components in the document though image segmentation using bounding boxes, nearest neighbors, linear regression (O'Gorman, 1993; Salleb & Hocini, 1996), we will translate the program status matrix into an integer-valued matrix, where green will be represented by 1, yellow by 0, and red by -1. An example of such a representation is presented in Figure 3. We will also parse DAES files to extract all the words used in the *program status* and *issue summary*. We will use Java text extraction libraries that have proven to be powerful. Hence, a report will be defined by the following components: MDAP name, Month, Year, status matrix, and the extracted text from the program status description and from the issue summary.



Item	M_3	M_2	M_1	Current	P_1	P_2	P_3	P_4	P_5	…	P_8
Cost_APB	1	1	1	1	1	1	1	1	1	1	1
Cost_Contract	0	0	0	-1	-1	-1	-1	-1	1	1	1
Schedule_APB	0	0	0	0	0	0	0	0	0	0	0
Schedule_Contract	0	0	0	1	1	1	1	1	-1	-1	-1
Performance_APB	1	1	1	1	1	1	1	1	1	1	1
Performance_Contract	1	1	1	1	1	1	1	1	1	1	1
Funding_APB	1	1	1	1	1	1	1	1	1	1	1
Funding_Contract	1	1	1	1	1	1	1	1	1	1	1

Figure 3. Translation of Data to Integer-Valued Matrix

Advanced Text Analysis. Text from the program status and issue summary will be used to assess the health or status of the MDAP. We will extensively use word clouds in order to visualize the status of the MDAP as described in the corresponding text (see example of word cloud in Figure 4), while word clouds will provide a nice visualization tool that provides a general idea on the contents of the documents.

Figure 4. Example Issue Summary Word Cloud

Besides visualization, we will also extract n-grams (sequence of words) and concepts or topics from the text in order to identify the issues that an MDAP is going through. For this purpose, we will use *Topic Modeling* to discover the topics discussed in the corpus. The intuition behind topic modeling is that when program managers prepare to write their monthly reports, they first have in mind a set of topics to address. They fill in the DAES using words associated with the different topics. Topic modeling identifies which words have the greatest probability of occurring together, and posits an abstract topic that conditions these probabilities. After generating the topic models for the MDAP documents, each document can be represented as a subset of the total topics, each in a proportion dependent on the content words. For instance, a report can belong to the topic "delay in schedule" and also to a topic "gap in funding."

To preprocess the documents, we will strip all the non-content words, and keep only the free text. Words and characters that are removed include section and field names, person names, punctuation, digits, and stop-words. A topic model consists of a probability distribution over topics, and then for each topic, the probability of each word in the vocabulary. The parameters behind the probability distributions are treated as latent variables. By analyzing a set of observations (words in the documents), it is possible to recover the latent structure of the generative model. The particular model we use is based on Latent Dirichlet Allocation (LDA; Blei, Ng, & Jordan, 2003) with Gibbs Sampling. For the experiment, we will use the Stanford Topic Modeling tool kit (http://nlp.stanford.edu/software/tmt/tmt-0.4/), a machine learning toolkit for natural language processing tasks.

Initial Results on Task 2: Automated Data Extraction

As discussed previously, DAES reports include information of program performance in the form of text and image. Our current focus is to understand the textual descriptions in the reports. The "Issue summary" section in the report illustrates the local issues, if any, and possible actions to resolve them. We prepare the input file for the topic modeling tool by manually copying this information as records into a csv (comma separated value) file. Specifically, we created two input files, one with set of Issues (problems encountered by MDAPs as reported in the DAES) and the other with set of Actions (the tangible actions proposed by the MDAP program manager to alleviate the Issues). As described above, we preprocess the reports by stripping the non-content words, and only keep the free text. Words and characters that are removed include section and field names, person names, punctuation, digits, and stop-words.

We first train a classifier to automatically identify the Issues identified in the DAES reports. Using an input file for the program MDAP_A from the previous section with few (15) records of its issues from a single year, we trained a model that will classify contents into issue-related topics. The results were not informative as the data was small, and so we extended the input to include issues of all the reports of MDAP_A across the years. The increased data set resulted in words *like schedule, Funding, Launch, ground site*, and *control* to be the top words in individual topic list. Examination of the tool for consistent results is important, and this technically indicates the convergence of the model. Convergence is dependent on the number of iterations the model is executed, which in turn is dependent on the data size. For a data size of 100 plus records, convergence occurred at around 800 iterations. We tested our trained model on a few (30) records of the same MDAP_A program. Test results indicate the proportion of relevance of the record to each of the topics. In Figure 5, we describe an example record and the proportion to which the record is relevant to the five topics identified by the model: Schedule, Funding, Launch, Ground site, Cost Control. As shown, this record has a high proportion of the topic *Funding*.

Record	Schedule	Funding	Launch	Ground site	Cost Control
Funding is required to test modifications of X-interface. If this is not funded, a simulator will be used for the purpose. This will incur a cost impact on the MDAP_A program.	2.68E-05	0.999836	5.12E-05	5.96E-05	2.65E-05

Figure 5. Example Topic Distribution for an "Issue-Related" Record

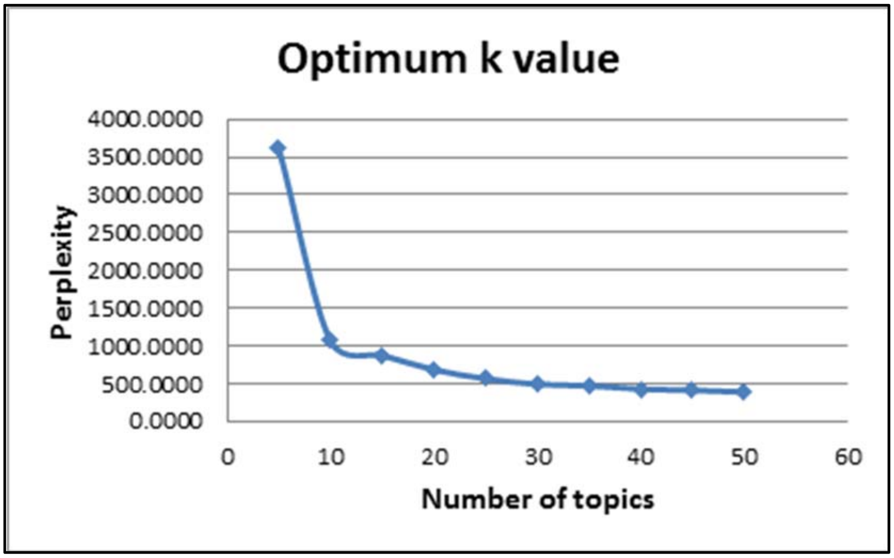


Figure 6. Determining Optimal k Value for an "Issue-Related" Topic

The number of topics is another important parameter for topic modeling. Initial results included five topics but finding optimum value for the number of topics will provide better results (Griffiths & Steyvers, 2004) in the sense that topics will be of finer granularity and hence more specific and relevant. For this we trained the model several times and recorded perplexity. Perplexity is a measure of the quality of the model learned by LDA in predicting future data from the same distribution as the data used to train the model. Lower perplexity value indicates a stable model. An experiment with the different number of topics, as shown in Figure 6, signifies that a k value of 20 or more is the best for our experimental data.

Our next steps in the task will involve the following:

- Automate the preparation of the input file using PERL, a scripting language.
- Expand the input data set to include reports of all the programs across the years and train the model with this data.

- Explore parameters of the LDA model to fine-tune the results such that the top set of words in a topic list is explanatory of that topic.
- Frame a phrase by analyzing the word list, for example, *Hardware issue* for better understanding and to support further analysis.
- Perform a similar topic extraction of "Action" related data.
- Scale the analysis to all MDAP programs.
- Use the extracted information to populate the Markov Decision Process in Task 4.
- Apply these topic extraction techniques to POM documents and compare it to the information in the SARS documents as discussed in Task 1.

Task 3: Local/Non-Local Issue Analysis

As part of automating the identification and analysis of local and non-local issues that lead to performance breaches, we will first evaluate the monthly mitigation forecasting for the problems from the DAES reports. We hypothesize that frequent forecasting failure along with sustaining/recurring breaches would require issue analysis. We plan to analyze the automatically extracted issues (Task 2) to reveal the presence or absence of local issues to explain the erroneous forecasting. If no significant issue can be found to explain the frequent forecasting failure, then we claim that either DAES reports do not capture the local reasons, or some non-local reasons are responsible for the poor performance. We will then analyze the local issues of the neighbors in the funding network to determine if there is any non-local issue that possibly could have propagated through the network leading to performance breaches. This is work that we will pursue after we make progress on Task 2.

Task 4: Formulate a Decision-Theoretic Model That Harnesses Decentralized-Markov Decision Process (DEC-MDP) Formalism

The questions to be addressed by this task are as follows:

- What are the essential characteristics of the MDAP network that justify a DEC-MDP model?
- How to model the MDAP network as a decentralized system?
- What are the key challenges in the design of the DEC-MDP?
- What essential features should the DEC-MDP model incorporate for better predictability?

In this work, decision-making in an MDAP network is viewed as a multiagent sequential decision problem because the utility gained by each agent depends on a sequence of actions over time. Our goal is to determine the behavior of the decision-makers (agents) that best balances the risks and rewards while acting in an uncertain environment with stochastic actions.

Each agent will make its individual decisions in an environment where the state space is not fully observable, meaning, that the nodes in the network (the programs) do not exactly know in which state they are in at any particular instant because they do not have complete information about their neighbors. With the partial state information, the individual agents aim to optimize the joint reward function. This class of problems is modeled as decentralized partially observable MDP (DEC-POMDP) in literature (Bernstein et al., 2002) where at each step when an agent takes an action, a state transition occurs, and the agent receives a local observation. Following this, the environment generates a global reward that

depends on the set of actions taken by all the agents. A necessary condition for stable equilibrium among agents in a multiagent system is that each agent plays a best-response to the strategy of every other agent: this is called a Nash Equilibrium. In our previous work (Cheng, Raja, & Lesser, 2012) we make the DEC-POMDP problem for a tornado tracking tractable by approximating the DEC-POMDP with a stochastic DEC-MDP model and using a factored reward function to define a Nash Equilibrium instead of the global reward function. We apply this technique to the MDAP domain. We define the reward function of this model to be composed of two different components: local reward function and global reward function. The local reward functions are dependent only on the individual agent's actions, while the global reward function depends on the action of all agents. We make this a stochastic DEC-MDP by defining a solution as a stochastic policy for each agent. A stochastic policy of an agent *i* is denoted by $\Pi_i(s) \in PD(A_i)$, where $PD(A_i)$, is the set of probability distributions over actions A_i. Stochastic policies can cope with the uncertainty of observation and perform better than deterministic policies in a partial observable environment. We plan to apply these modeling techniques we have developed for another complex multiagent domain (tornado tracking) to the MDAP domain.

Conclusions and Future Work

Our multi-year research goal is to gain a deeper understanding of interdependencies among MDAPs by examining the various information sources, SARS, DAES, POMS, and R-docs. This would involve establishing a statistically significant correlation between the state of MDAP network dependencies and their consequences. Our previous work in this area involved manual analysis of DAES and SARS data belonging to a small network MDAPs to determine the local and non-local issues that affect MDAP performance. As a consequence of this work, we recognized the need to analyze the data from the entire set of MDAPs in batch form to be able to build good decision models for "what-if" analysis. The volume and complexity of the data has led to our current research tasks that involve automating methods for data extraction, network analysis, and decision model construction for successful and not-so-successful MDAPs. In this paper, for each task, we describe our proposed work and initial results. Our hope is that as a consequence of this work, we will be able to (1) extract the link characteristics between MDAPs; (2) examine and compare the funding network structure characteristics of interdependent regions belonging to successful and not-so-successful MDAPs to augment our current work in "what-if" analyses; (3) automate the data extraction and analysis process by leveraging algorithms for decision support as well as image and text analysis; and (4) continue to identify the challenges in acquiring the data from the government and program managers.

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Lexical Link Analysis Application: Improving Web Service to Acquisition Visibility Portal

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Abstract

DoD acquisition is an extremely complex system, comprised of myriad stakeholders, processes, people, activities, and organizational structures. Processes within this complex system are encumbered by the continuous development of large amounts of unstructured and unformatted acquisition program data, difficult to aggregate across the "enterprise." Yet acquisition analysts and decision-makers must analyze all types and spectrums of the available data to obtain a complete and comprehensible picture. This can be a daunting task. We have applied a data-driven automation system and methodology, namely, lexical link analysis (LLA), to facilitate acquisition researchers and decision-makers to recognize important connections (concepts) that form patterns derived from dynamic, ongoing data collection, analysis, and decision making. LLA technology and methodology is used to uncover and display relationships among competing programs and Navy-driven requirements. In the past year, we tested our method using samples of acquisition data for visualization and validity. LLA successfully discovered statistically significant correlations, and automatically extracted lexical links, thus improving acquisition professionals' knowledge of their data. This might have otherwise required expensive manpower to perform. We also developed LLA into a web service via several use cases for large-scale LLA applications. In this paper, we show how to apply the LLA web service to the Acquisition Visibility Portal, which is a critical tool to provide the DoD-wide acquisition community with authoritative and accurate data services. The resulting methodology could reduce the workload of decision-makers and achieve improved purchasing decisions, serving to improve the long-term success of acquisition strategies.

Introduction

Acquisition research has increased in component, organizational, technical, and management complexity. It is difficult for acquisition professionals to remain continuously aware of their decision-making domains because information is overwhelming and dynamic. According to the *Chairman of the Joint Chiefs of Staff Instruction for Joint Capabilities Integration and Development System* (JCIDS; CJCS, 2009), there are three key processes in the DoD that must work in concert to deliver the capabilities required by the warfighters: the requirements process; the acquisition process; and the Planning, Programming, Budget, and Execution (PPBE) process.

Each process produces a large amount of data in an unstructured manner; for example, the warfighters' requirements are documented in Universal Joint Task Lists (UJTLs), Joint Capability Areas (JCAs), and Urgent Need Statements (UNSs). These requirements are processed in the JCIDS to become projects and programs, which should result in products such as weapon systems that meet the warfighters' needs. Program data are stored in the Defense Acquisition System (DAS). Programs are divided into Major DoD Acquisition Programs (MDAPs), Acquisition Category II (ACATII), and so forth. Program Elements (PEs) are the documents used to fund programs yearly through the congressional budget justification process. Data is too voluminous, too unformatted, and too unstructured to be easily digested and understood—even by a team of experienced acquisition professionals.

On a conceptual level, our first question is as follows: How can the information that emerges from the acquisition process be used to produce overall awareness of the fit between programs, projects, systems, and of the needs for which they were intended?

In precise terms, we observed that there were three important processes that seemed fundamentally disconnected. Specifically, they were the congressional budgeting justification process (such as information contained within the PEs), the acquisition process (such as information in the MDAP and ACATII), and the warfighters' requirements (such as information in UNSs and in UJTLs), as shown in Figure 1. Yet, these were not analyzed and compared together in a dynamic, holistic methodology that could keep pace with changes and reflect patterns of relationships. In the past three years, we employed the lexical link analysis (LLA) automation methodology to analyze the data in three areas, illustrated in Figure 1.

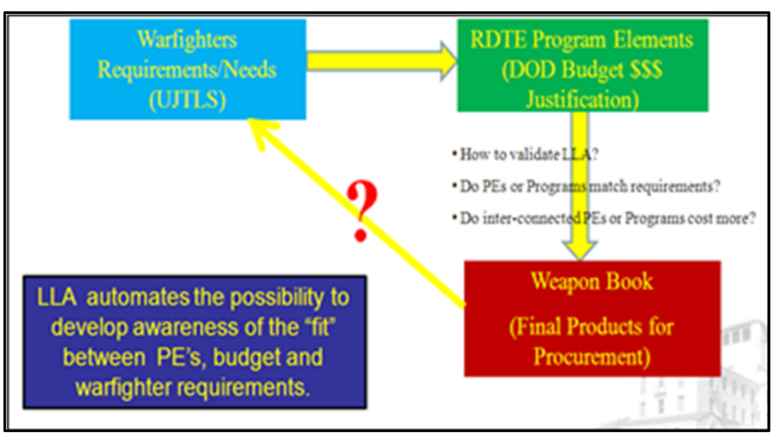

Figure 1. Determining Business Processes Links From Requirements to DoD Budget Justification to Final Products

In the past, we have explored how analytic and visualization tools such as LLA can help detect data inconsistency and gaps (bad data; see Research Status section). We have further systematically improved our understanding of the quality of the data by automatically discovering new patterns that were previously unknown, and identified data dependencies that might be indicators for program or investment performances. However, much more work is needed in this area as well as continued in-depth analysis performed at the different levels of the Acquisition Visibility Portal (AVP). AVP is a critical tool that provides the DoD-wide acquisition community with authoritative and accurate data services via interfaces to DTIC and DAMIR for programs (e.g., MDAPs, ACATIIs) with milestones, costs, schedules and performance data, Selected Acquisition Reports (SARs), and Acquisition Strategy Reports (ASRs), among others.

We seek to show how LLA can be adapted to the AVP's ongoing requirements and continuous improvement of DoD data quality and decision-making.

Methodology

Overview of Lexical Link Analysis

As in military operations, where the term *situational awareness* was coined, we note that our efforts can inform awareness of analyzed data in a unique way that helps improve a decision-maker's understanding or awareness of its content. We therefore define *awareness* as the cognitive interface between decision-makers and a complex system, expressed in a range of terms or "features," or specific vocabulary or "lexicon," to describe the attributes and surrounding environment of the system. Specifically, LLA is a form of text mining in which word meanings represented in lexical terms (e.g., word pairs) can be represented as if they are in a community of a word network.

Link analysis "discovers" and displays a network of word pairs. These word pair networks are characterized by one-, two-, or three-word themes. The *weight* of each theme is determined by its frequency of occurrence. Figure 2 shows a visualization of common lexical links shared between Systems 1 and 2, shown in the red box. Unlinked, outer vectors (outside the red box) indicate unique system features. For example, Figure 3 shows the information from three categories that can be compared, and Figure 4 shows the information from two time periods that can be compared.

Each node, or word hub, represents a system *feature*, and each color refers to the collection of lexicon links (features) that describes a concept or theme. The overlapping area nodes are *lexical links*. What is unique here is that LLA constructs these linkages via intelligent agent technology using social network grouping methods.

The closeness of the systems in comparison can be visually examined or examined using the Quadratic Assignment Procedure (QAP; Hubert & Schultz, 1976; e.g., in UCINET; Borgatti, Everett, & Freeman, 2002) to compute the correlation and analyze the structural differences in the two systems, as shown in Figure 5.

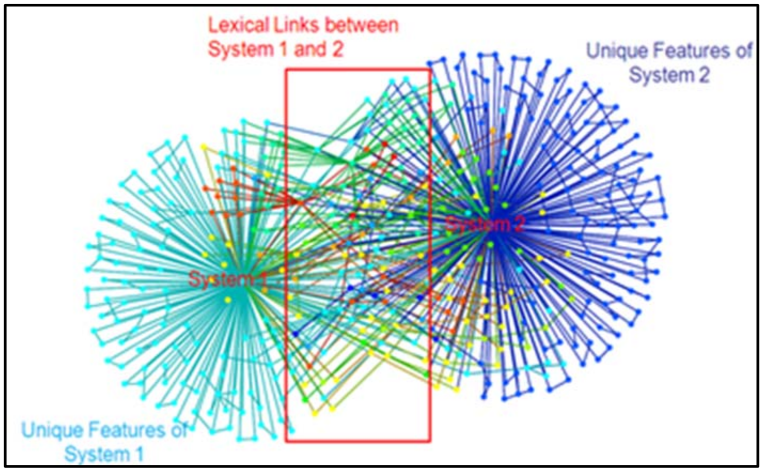

Figure 2. Comparing Two Systems Using LLA

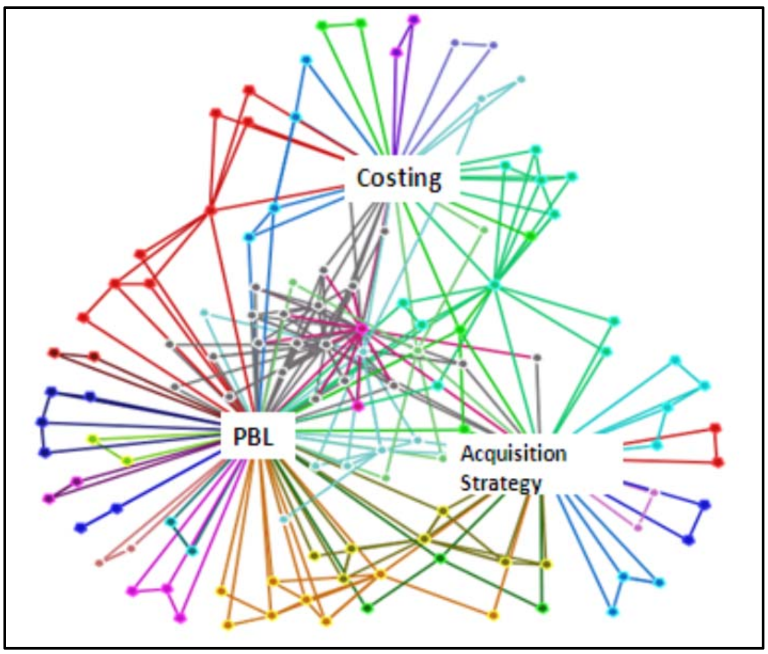

Figure 3. Comparing Three Categories Using LLA

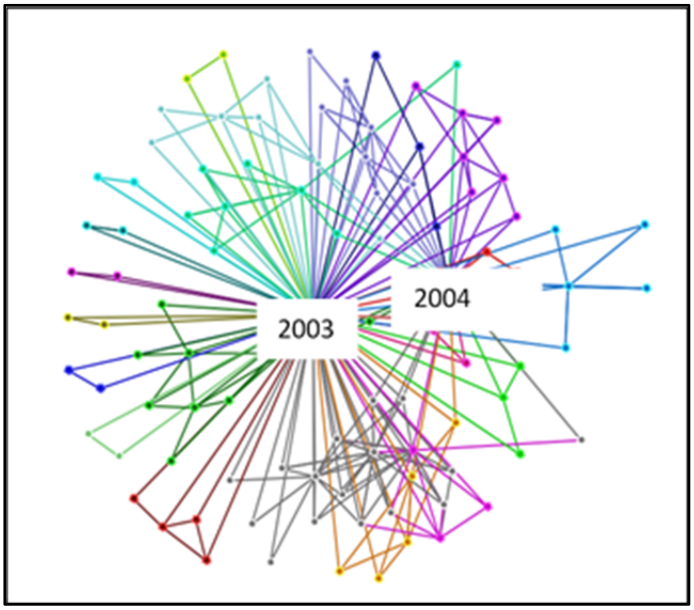

Figure 4. Comparing Two Time Periods

QAP Correlations

		1 lla_n	2 lla_n	3 lla_n	4 lla_n	5 lla_n	6 lla_n	7 lla_n	8 lla_n
1	lla_network_1_2010-AcquisitionStrategy	1.000	0.174	0.156	0.155	0.036	0.111	0.020	0.062
2	lla_network_1_2003-AcquisitionStrategy	0.174	1.000	0.447	0.149	0.052	0.119	0.043	0.089
3	lla_network_1_2004-AcquisitionStrategy	0.156	0.447	1.000	0.111	0.047	0.119	0.051	0.080
4	lla_network_1_2005-AcquisitionStrategy	0.155	0.149	0.111	1.000	0.156	0.084	0.034	0.088
5	lla_network_1_2006-AcquisitionStrategy	0.036	0.052	0.047	0.156	1.000	0.067	0.036	0.056
6	lla_network_1_2007-AcquisitionStrategy	0.111	0.119	0.119	0.084	0.067	1.000	0.097	0.123
7	lla_network_1_2008-AcquisitionStrategy	0.020	0.043	0.051	0.034	0.036	0.097	1.000	0.286
8	lla_network_1_2009-AcquisitionStrategy	0.062	0.089	0.080	0.088	0.056	0.123	0.286	1.000

QAP P-Values

		1 lla_n	2 lla_n	3 lla_n	4 lla_n	5 lla_n	6 lla_n	7 lla_n	8 lla_n
1	lla_network_1_2010-AcquisitionStrategy	0.000	0.020	0.020	0.020	0.020	0.020	0.020	0.020
2	lla_network_1_2003-AcquisitionStrategy	0.020	0.000	0.020	0.020	0.020	0.020	0.020	0.020
3	lla_network_1_2004-AcquisitionStrategy	0.020	0.020	0.000	0.020	0.020	0.020	0.020	0.020
4	lla_network_1_2005-AcquisitionStrategy	0.020	0.020	0.020	0.000	0.020	0.020	0.020	0.020
5	lla_network_1_2006-AcquisitionStrategy	0.020	0.020	0.020	0.020	0.000	0.020	0.020	0.020
6	lla_network_1_2007-AcquisitionStrategy	0.020	0.020	0.020	0.020	0.020	0.000	0.020	0.020
7	lla_network_1_2008-AcquisitionStrategy	0.020	0.020	0.020	0.020	0.020	0.020	0.000	0.020
8	lla_network_1_2009-AcquisitionStrategy	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.000

QAP statistics saved as datafile QAP Correlation Results

Figure 5. QAP Correlation via UCINET

Figure 6 shows a visualization of LLA with connected keywords or concepts as groups or themes. Words are linked as word pairs that appear next to each other in the original documents. Different colors indicate different clusters of word groups. They were produced using a link analysis method—a social network grouping method (Girvan et al., 2001) where words are connected, as shown in a single color, as if they are in a social community. A "hub" is formed around a word centered or connected with a list of other words ("fan-out" words) centered on other hub words. For instance, Figure 7 shows a detailed view of a theme or word group in Figure 6: the words "analysis, research, approach" are connected and centered around other related words. We use three words such as "analysis, research, approach" to label a group.

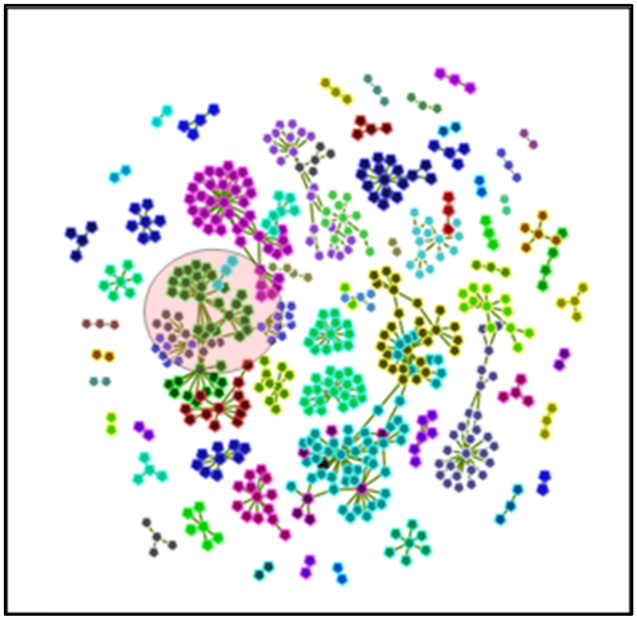

Figure 6. Word and Term of Themes Discovered and Shown in Colored Groups

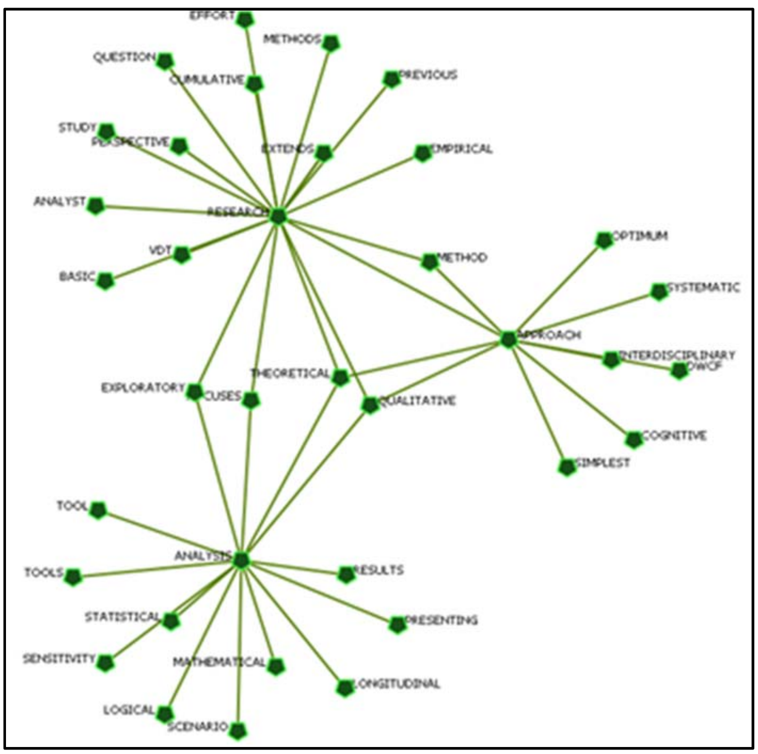

Figure 7. A Detailed View of a Theme or Word Group From Figure 6

The detailed steps of LLA processing include applying collaborative learning agents (CLAs) and generating visualizations, including a lexical network visualization via AutoMap (2009), radar visualization, and matrix visualization (Zhao, Gallup, & MacKinnon, 2010). The following are the steps for performing an LLA:

- Read each set of documents.

- Select feature-like word pairs.
- Apply a social network community finding algorithm (e.g., Newman grouping method; Girvan et al., 2001) to group the word pairs into themes. A theme includes a collection of lexical word pairs connected to each other.
- Compute a "weight" for a theme for the information of a time period, that is, how many word pairs belong to a theme for that time period and for all time periods.
- Sort theme weights by time, and study the distributions of these themes by time.

Business Problems That LLA Addresses

General areas that LLA usually informs are the following:

- Discovering themes and topics in the unstructured documents and sorting the importance of the themes
- Discovering social and semantic networks of organizations that were involved, comparing the two networks to obtain insights to answer the following questions:
    - Demonstrating what were the organizations involved in the *important* themes
    - Illustrating how semantic networks might suggest improved potential collaboration when compared to social networks

Social and Semantic Networks Analysis

Current research of social network analysis mostly focuses on people or organizations of direct associations, regardless of the contents linked. The so-called study of centrality (Girvan, 2002; Feldman, 2007) has been a focal point for the social network structure study. Finding the *centrality* of a network lends insight into the various roles and groupings such as the connectors (e.g., mavens, leaders, bridges, isolated nodes), the clusters (and who is in them), the network core, and its periphery. We have been working toward two areas of innovations in the network analysis:

- Extracting social networks based on the entity extraction
- Extracting semantic networks based on the contents and word pairs using LLA
- Applying characteristics and centrality measures from the semantic networks and social networks to predict latent properties such as emerging leadership, for example, emerging techniques that might dominate, in the social networks. These characteristics are further categorized into themes and time-lined trends for informed prediction of future events.

Implementation Details

In the past year, we continued our efforts at the Naval Postgraduate School (NPS) by using CLAs (Quantum Intelligence [QI], 2009) and expanded to other tools, including AutoMap (Center for Computational Analysis of Social and Organizational Systems [CASOS], 2009) for improved visualizations. Results from these efforts arose from leveraging intelligent agent technology via an educational license with Quantum Intelligence,

Inc. CLA is a computer-based learning agent, or agent collaboration, capable of ingesting and processing data sources.

We have been generating visualizations including a lexical network visualization using various open source tools. We began by using the Organizational Risk Assessment (ORA; CASOS, 2009) tool and expanded to other tools. For example, in the past year, we developed 3-D network views using Pajek (2011) and X3D (2011). We also developed our visualizations Radar view and Match view (Zhao et al., 2010).

LLA uses a computer-based learning agent called Collaborative Learning Agents (CLA; QI, 2009) to employ an unsupervised learning process that separates patterns and anomalies. CLA is a computer-based learning agent, or agent collaboration, capable of ingesting and processing data sources, leveraged via an educational license with Quantum Intelligence, Inc. The unsupervised agent learning is implemented by indexing each set of documents separately and in parallel using multiple learning agents. Multiple agents can work collaboratively and in parallel. We set up a cluster utilizing Linux servers in the NPS High Performance Computing Center (HPC) to handle the large-scale data and secure environment in the NPS Secure Technology Battle Laboratory (STBL).

Relations to Other Methods

The LLA approach is more properly related to Latent Semantic Analysis (LSA; Dumais, Furnas, Landauer, Deerwester, & Harshman, 1988) and Probabilistic Latent Semantic Analysis (PLSA). In the LSA approach, a term-document matrix is the starting point for analysis. The elements of the term-document or feature-object (term as feature and document as object) matrix are the occurrences of each word in a particular document, that is, $A = [a_{ij}]$, where a_{ij} denotes the frequency in which term *j* occurs in document *i.* The term-document matrix is usually sparse. LSA uses singular value decomposition (SVD) to reduce the dimensionality of the term-document matrix. SVD cannot be applied to the cases where the vocabulary (the unique number of terms) in the document collection is large. LSA has been widely used to improve information indexing, search/retrieval, and text categorization.

A recent development related to this method is called latent Dirichlet allocation (LDA; Blei, Ng, & Jordan, 2003), which is a generative probabilistic model of a corpus. In LDA, a document is considered to be composed of a collection of words—a “bag of words,” where word order and grammar are not considered important. The basic idea is that documents are represented as random mixtures over latent topics, where each topic is characterized by a statistical distribution (Dirichlet distribution) over the corpus. Our theme generation from LLA is different than LDA, in which a collection of lexical terms are connected to each other semantically, as if they are in a social community, and social network grouping methods are used to group the words, and unlike LSA, our method is easily scaled to analyze a large vocabulary and is generalizable to any sequential data.

Anticipated Benefits

Our LLA method provides the solutions to meet the critical needs of the acquisition research. The key advantage is to provide an innovative near real-time self-awareness system to transfer diversified data services into strategic decision-making knowledge, specifically through the following:

- Automation: High correlation of LLA results—with the link analysis done by human analysts—makes it possible to save human power and improve responsiveness. Automation is achieved via computer program or software *agents* to perform LLA frequently, and in near real-time.

- Discovery: LLA "discovers" and displays a network of word pairs. These word pair networks are characterized by one, two, or three word themes. The weight of each theme is determined based on its frequency of occurrence. It may also discover blind spots of human analysis that are caused by the overwhelming data for human analysts to consider.
- Validation: LLA may provide different perspectives of links. In the acquisition context, links discovered by human analysts may emphasize component and part connections that do not necessarily reflect content overlaps. LLA looks for the overlapping of contents to help identify improved affordability and improved response to meeting warfighter requirements, and achieve better acquisition decisions. Consequently, it can provide improved results in terms of trust and quality of association discovery and can help break through the taxonomy of ignorance (Denby & Gammack, 1999) and organizational boundaries, and help improve organizational reach.

Research Status

Acquisition Visibility Portal Background

Our goal is to demonstrate the LLA web service for assisting the DoD-wide effort of integrating and maintaining authoritative and accurate acquisition data services in both legacy and new platforms. Specifically, we wanted to analyze the data sources from the Acquisition Visibility Portal (https://portal.acq.osd.mil) by examining consistency, correlation, and gaps among categories of information for each individual program listed in the portal.

One of the biggest risk factors in defense acquisition is the unanticipated effects of program interactions. For example, ASD(SE) and Dahmann worked toward identifying interdependence among programs within a system of systems (SoS). Yet, more broadly, and as a result of required joint capabilities, portfolios often include program interdependencies and system-of-systems effects. Ultimately, the current "program-centric" acquisition paradigm is increasingly ill-suited to identify and address program risks that arise outside of program boundaries. LLA can help isolate these issues from the body of information collected, which have yet to be effectively identified.

To begin to address this risk, we observed that very little of the information generated for program oversight is amenable to effective analysis. Every major acquisition program's milestone review generates volumes of information, which the OSD staff is supposed to review to determine if the program is properly prepared for the next milestone. Although they are beginning to compile these artifacts centrally to facilitate review and analysis, at present, the only way to analyze the information in these artifacts is to read them. With limitations on staffing, little time is available to thoroughly review these artifacts. Moreover, each functional community is required to review only the particular document for which it is responsible. For example, the systems engineering community typically only examines the Systems Engineering Plan (SEP), the test and evaluation community looks only at the Test & Evaluation Master Plan (TEMP), and the acquisition community looks at the Acquisition Strategy Report (ASR). Rarely do any of these stakeholders review multiple reports or jointly discuss them to determine if they are mutually consistent and to consider inconsistencies that might indicate programmatic risk. There is even less incentive and opportunity to look for external factors that would potentially invalidate the assumptions that underpin the basic cost, schedule, and performance targets of each program execution.

Overlaying the concept maps for each of the major categories of artifacts to conduct a pair-wise comparison might expose significant disconnects between them. We are motivated by a situation in which the SEP identifies a critical dependency between the

program and an external system, but the TEMP doesn't have a corresponding reference to testing that interdependency. Therefore, it may be productive to compare the acquisition strategy to the SEP or TEMP.

Results

LLA maps of these artifacts from one category to another, for example, the SEP at Milestone B, are significantly different from the SEP at Milestone C that might indicate a reduction in system functionality resulting from cost increases elsewhere. These maps, reported as themes, concepts, and word pairs, may help cue a decision-maker's attention to the potential issues and help the decision-maker consider specific and productive directions for further scrutiny.

To develop comprehensive LLA maps, we first extracted a sample from a representative MDAP from the Acquisition Visibility Portal (AVP) with categories of information to demonstrate the method, as follows:

- SEP: 2 documents, 222 pages
- TEMP: 5 documents, 62 pages
- ASR: 11 documents including metrics, 634 pages
- SARs: 9 documents, 313 pages
- DAES: 19 documents, 447 pages
- Milestone B 2366b Certification Acquisition Decision Memorandum (ADM) 12 documents, 105 pages
- APB: 3 documents, 39 pages
- TRA: 1 document, 1 page

Figure 8 lists the top 20 themes discovered for comparing data for ASR and SEP with the highest correlations. In Row 2, there are 299 word pairs for the two sources together classified in Theme 117(E); 47 of them appear in both sources, indicating potential feature overlaps. The *correlation* is the ratio=47/299=0.157 which indicates 15.7% of the features represented as word pairs shared in both artifacts. As a detail shown in Figure 9, part of 299 word pairs in Theme 117(E) are visualized in red, yellow, and green links, representing the shared word pairs, unique ones to ASR and SEP, respectively.

1	Theme Id	All Sources	_ASR	_SEP	Overlap	Correlation
2	117(E)	299	201	51	47	0.157
3	347(P)	481	346	67	68	0.141
4	395(P)	500	330	102	68	0.136
5	130(P)	590	428	89	73	0.124
6	281(P)	469	372	42	55	0.117
7	210(P)	570	400	105	65	0.114
8	298(P)	599	348	184	67	0.112
9	388(P)	508	381	73	54	0.106
10	263(P)	666	517	79	70	0.105
11	368(P)	669	472	127	70	0.105
12	330(P)	546	391	99	56	0.103
13	147(E)	234	181	29	24	0.103
14	224(E)	331	236	62	33	0.100
15	144(P)	490	350	92	48	0.098
16	270(P)	502	371	82	49	0.098
17	235(E)	431	329	60	42	0.097
18	245(E)	281	215	39	27	0.096
19	113(E)	334	245	57	32	0.096
20	310(P)	586	441	90	55	0.094
21	182(A)	197	157	22	18	0.091

Figure 8. Themes for Comparing SEP and ASR, Sorted According to Correlation Ascending

Figure 9 shows that there are concepts related to these word nodes that appear uniquely to the ASR or SEP.

Since the SEP document is supposed to support the ASR, the illustrations and visualizations of it might inform acquisition professionals about why concepts in the SEP were missing from the ASR, and vice versa.

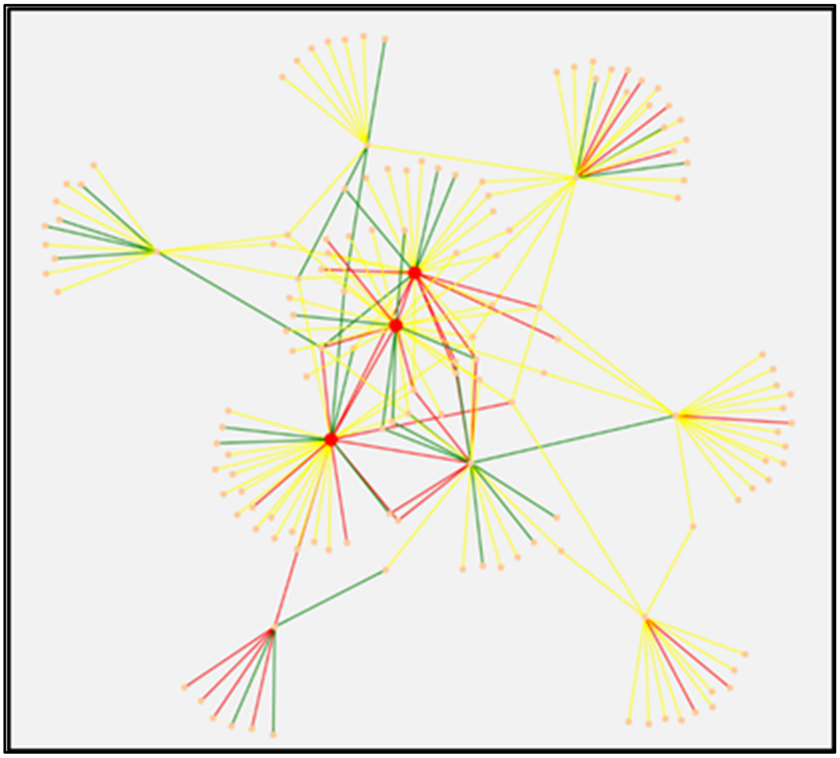

Figure 9. Detail of Word Pairs for Theme 117(E): Red Links for Shared Word Pairs for SEP and ASR (Yellow Links for Unique Word Pairs Unique to ASR, and Green links for Unique Word Pairs Unique to SEP)

Figure 10 lists the least correlated themes discovered for comparing data for ASR and SEP. In Row 2, there are 149 word pairs for the two sources together, classified in Theme 359(E)(A); four of them appear in both sources (overlap). The correlation is the ratio=4/149=0.027. A detail shown in Figure 9, part of 149 word pairs in Theme 359(A) are visualized in red, yellow, and green links, representing the shared word pairs, unique ones to the ASR and SEP, respectively.

1	Theme Id	All Sources	ASR	SEP	Overlap	Correlation
2	359(A)	149	127	18	4	0.027
3	390(A)	173	150	18	5	0.029
4	419(A)	95	73	18	4	0.042
5	267(A)	149	123	19	7	0.047
6	238(A)	170	121	41	8	0.047
7	293(A)	231	184	36	11	0.048
8	76(E)	249	208	28	13	0.052
9	408(E)	419	376	21	22	0.053
10	287(A)	223	187	24	12	0.054
11	203(E)	259	170	75	14	0.054
12	334(E)	276	218	43	15	0.054
13	135(E)	271	218	38	15	0.055
14	104(A)	196	163	22	11	0.056
15	63(E)	314	253	43	18	0.057
16	373(P)	480	403	49	28	0.058
17	372(P)	608	509	62	37	0.061
18	389(A)	155	137	8	10	0.065
19	331(E)	383	246	112	25	0.065
20	205(P)	561	420	104	37	0.066
21	127(P)	490	414	43	33	0.067

Figure 10. Themes for Comparing SEP and ASR, Sorted According to Descending Correlation

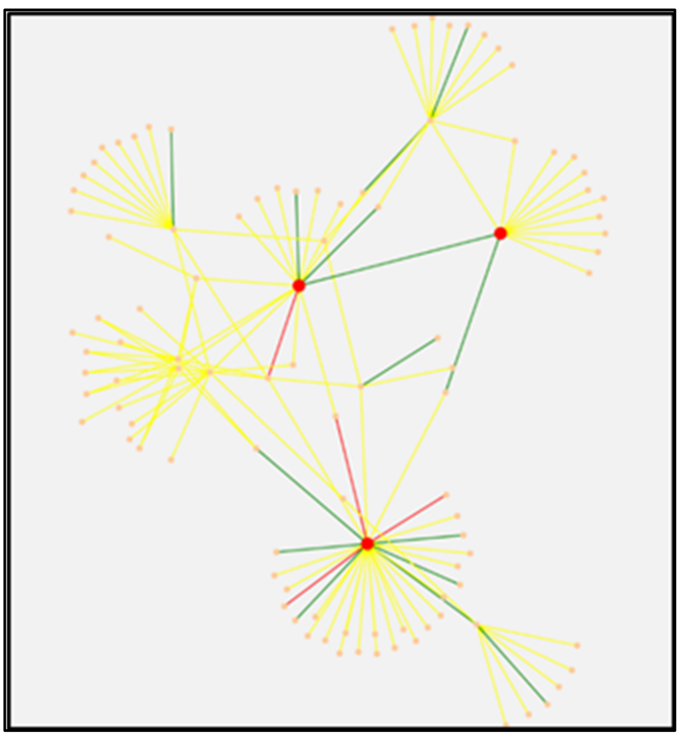

Figure 11. Detail of Word Pairs for Theme 359(A): Red Links for Shared Word Pairs for SEP and ASR (Yellow Links for Unique Word Pairs Unique to ASR, and Green Links for Unique Word Pairs Unique to SEP)

In Figure 11, there are also concepts that are more prevalent in the ASR than in the SEP. The ASR includes other concepts that are not in the SEP that might be important.

LLA also categorizes themes into popular (P), emerging (E), and anomalous (A). Comparing Figure 8 and Figure 10, one can see that popular themes tend to have higher correlations among data sources (ASR and SEP), while anomalous themes tend to have lower correlations among data sources.

For each pair of comparisons for two categories of information, we use the ratio of the number of word pairs that appear in both categories and the total number of word pairs as an overall correlation for each pair.

In Table 1, the highlighted cells are the ones with correlation > 0.06. The categories DAES, SARs, and SEP have higher overall correlations with other ones. The most correlated two categories are SARs and DAES (correlation = 0.117). The category TEMP has the lowest overall correlations with other categories. Although TEMP and SEP were both produced in the test and evaluation community, the correlation between the two is low (0.027).

Table 1. LLA Correlations Between Categories of Information

	APB	ASR	2366B_Cert	DAES	SARs	SEP	TEMP	TRA
APB	1.000	0.007	0.027	0.022	0.080	0.014	0.010	0.005
ASR	0.007	1.000	0.015	0.048	0.025	0.075	0.028	0.001
2366B_Cert	0.027	0.015	1.000	0.026	0.038	0.026	0.018	0.068
DAES	0.022	0.048	0.026	1.000	0.117	0.073	0.023	0.003
SARs	0.080	0.025	0.038	0.117	1.000	0.044	0.020	0.004
SEP	0.014	0.075	0.026	0.073	0.044	1.000	0.027	0.003
TEMP	0.010	0.028	0.018	0.023	0.020	0.027	1.000	0.002
TRA	0.005	0.001	0.068	0.003	0.004	0.003	0.002	1.000

When discussing the findings with the domain expert, it seems the correlation is surprisingly low for DAES and SARs. DAES and SARs reports are similar in context and content (both relate to acquisition performance); they would be expected to have higher correlation. Further investigations, such as the following: are needed to see what might be the causes for the low correlation:

- To investigate if significantly different content appears in the two types of reports; for example, DAES reports may include more details than SARs reports.
- To differentiate the SAR and DAES reports by year and compute the correlations over time, to see when the significant discrepancies, that is, the drop in the correlation, came into the picture.
- To correlate the DAES or SAR reports over time separately to see if the correlation increases and decreases might have to do with the new features being introduced into the program, and therefore correlate to the significance of low or high changes found in LLA with the numeric metrics such as cost, schedule, funding, and performance.

Future Work

Since this is the first program to have undergone a relatively comprehensive LLA analysis using multiple types of acquisition documents, the findings cannot be evaluated in

terms of being “good” or “bad,” “normal” or “unusual,” and so forth. Therefore, future investigation should consider the following additional studies:

- Analyze additional programs in the AVP, compute the correlation matrices like Table 1, and compare the results to determine if the correlation patterns are similar or different.
- Discuss the findings in detail with the domain experts and personnel associated with the programs to see if the correlation patterns have significance, as follows:
  - if the correlation are the indications for data quality issues and
  - if the correlation patterns have impacts for the costs, schedules, funding, and performance of the programs.

Conclusion

In this paper, we demonstrated how to apply LLA to generate maps of the acquisition artifacts among multiple categories of data. These maps, reported as themes, concepts, and word pairs, may help identify the issues and offer specific and productive directions for further examination as to why there are gaps among the categories of information.

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Capturing Creative Program Management Best Practices[1]

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Abstract

This research attempted to capture the creative aspects of government program management in three specific areas: efficiently navigating oversight, capturing the intent of regulations, and developing innovative risk management practices. Respected acquisition leaders with diverse backgrounds and experiences were interviewed with ranks ranging from 0-6 to 0-8 and GS-15 to SES. Several contractor interviews were conducted for specific purposes. The data were iteratively coded and analyzed using ATLAS.ti. The results were categorized into four themes, each with three sub-elements. Differences between respondents with program director experience and those with rapid acquisition experience are discussed. A survey was then distributed to the interviewees and junior acquisition professionals. The predominant research finding is that senior acquisition professionals believe that relationship-building is of paramount importance. This, along with creative practices regarding how to externally communicate program strategies, greatly increases the probability of successfully navigating oversight and obtaining waivers or tailoring regulations. Various risk management techniques and management reserve techniques are presented. In addition, knowledge gaps between the junior acquisition workforce and senior leaders were identified based on statistical significance and corrective actions recommended where applicable. Reports and outbriefs were developed, tailored to each class, to relay these creative practices to junior acquisition professionals.

Introduction

This paper presents the results of exploratory thesis research regarding creative program management practices as identified by senior leaders. For the purposes of this paper, *creative* is defined as any innovative, resourceful, uncommon, or out-of-the-box thinking and practices leading to efficient and effective program management without jeopardizing integrity, ethics, or laws. The literature review identified three areas of investigation:

Topic 1: How to creatively reduce non value-added oversight
Topic 2: How to creatively capture the *intent* of regulations
Topic 3: Creative practices of resource-loaded risk management

The first two topics are the focus of this paper because they led to the overarching findings. Interviews with respected, leading practitioners representing diverse programs with

[1] This study is an original product developed from thesis research conducted at the Air Force Institute of Technology (AFIT) in partial fulfillment of a Master of Science in Research and Development Management. This research has not been previously published and is not under consideration by another journal for publication.

varying sizes and complexity were conducted. A survey was then distributed to government acquisitions personnel, further validating interview findings with quantitative data, as well as prioritizing responses from senior leaders and identifying the major differences in the junior workforce.

Literature Review

Perhaps the greatest impediment to the achievement of high quality—and productivity—is … burgeoning bureaucracy.
(Augustine, 1997, p. 79)

The type of oversight described in this paper must be defined because "oversight" can have various meanings based on the reader's experiences. For the purposes of this research, oversight consists of the organizations and people needed to approve (either formally or informally) a program's approach and/or documentation to proceed to the next phase in the acquisition life cycle. This is separate from government oversight of contractors or prime contractor oversight of subcontractors. This research is not meant to make judgments as to the goodness of oversight or to assess the theory of checks and balances versus optimal efficiency. The goal is to identify creative ways in which DoD acquisition oversight can be made more beneficial or, in situations when oversight is overly cumbersome, how it can be effectively navigated with minimal effort.

Setting the Stage: Extensive Oversight—A Serious Issue

Acquisition oversight began in the 1960s (Acker, 1993). Numerous studies and reports on defense acquisition have subsequently been conducted over the past five decades. A common theme extracted from these reports is that a serious problem exists with extensive, non-required, and, many times, non value-added oversight. One panel of experts estimated the cost of oversight in Air Force programs to be as high as $94 million (Neal, 2004). Knue's (1991) thesis is recommended as a detailed source for explaining oversight of and within the DoD. Additionally, several case studies exist on oversight within Air Force programs. A few of the more prominent reports are summarized in the following paragraphs.

Miller and Williams (1993) conducted a case study of oversight in the C-17 program. The interviews they conducted revealed that oversight had a negative effect on program management and morale. There was "absolute certainty in the collective consciousness" of members of the C-17 program office that a link exists between oversight and its effect on cost and schedule performance (Knue, 1991, p. 72). Interviewees also cited external (outside the chain of command) sources of oversight from nine distinct organizations that negatively affected the program. These nine external sources did not include legislative, executive, and media oversight (Miller & Williams, 1993).

A RAND study of the B-1B bomber program concluded that an extraordinary amount of internal and external coordination was required, leading to a "ceaseless series of meetings, calls, and memos" (Bodilly, 1993, p. 40). The study concluded that 14 different groups had major roles in the program.

The *Beyond Goldwater-Nichols* Phase 2 Report (Murdock et al., 2005) stated that the "well-intentioned majority of the acquisition corps today faces two significant types of bureaucratic impediments: highly centralized oversight and conflicting guidance" (p. 91). The Phase 2 Report also found that program managers (PMs) and program executive officers (PEOs) are left with about 50% or less of their time to actually manage their programs (Murdock et al., 2005).

The highly regarded Defense Acquisition Performance Assessment (DAPA) report in 2006 showed that 97% of the survey inputs received indicated that the current oversight and leadership process is deficient (Kadish et al., 2006). Figure 1, from the DAPA report, highlights the key issues affecting government acquisitions. As can be seen in the figure, respondents viewed oversight as the most prevalent issue.

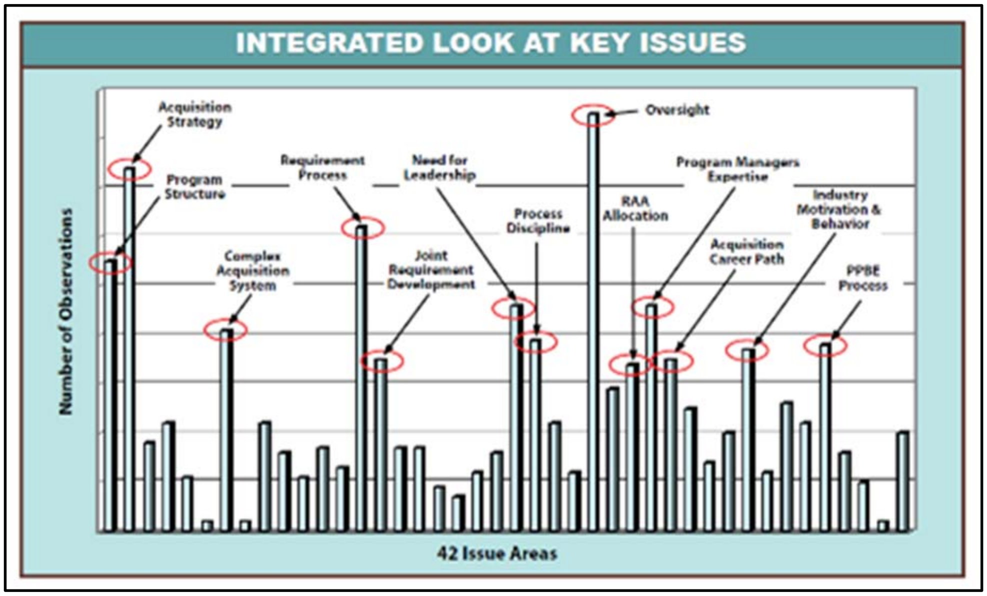

Figure 1. Integrated Look at Key Issues
(Kadish et al., 2006)

Oversight is discussed in several sections of the DAPA report. Figure 2 is a one-page summary of the myriad DAPA findings with respect to oversight. Issues relating to oversight are divided into four categories: Extent of Oversight, Programmatic Issues, Accountability/Authority Issues, and Effect on Progress.

Extent of oversight

- Current oversight process is burdensome, ineffective, adds little value, and inhibits steady improvement
- Excessive numbers of reviews and oversight personnel; quantity replaced quality
- Regulations written to implement policy are more stringent than the policy itself
- Dissatisfaction with sheer volume of acquisition laws, regulations, and policies
- Rely on overlapping layers of reviews at the expense of focus and quality

Programmatic Issues

- Acquisition Category (ACAT) designation process results in excessive number of programs requiring additional level of DAB approvals, causing excessive reporting requirements
- Even with the laborious and extensive oversight, troubled programs still pass through
- Lack of continuity or attendance on OSD acquisition IPTs results in the re-emergence of issues previously resolved and revisiting decisions
- Policy and guidance often conflict, resulting in ignoring policy or seeking legal advice
- Institutional biases toward waiving or tailoring regulations (even though DoD Directives promote tailoring for each program's situation)

Accountability/Authority Issues

- Oversight is preferred to accountability and based on a lack of trust
- Oversight dilutes or eliminates accountability for program performance
- PMs effectiveness is constrained by people who do not share responsibility or accountability
- OSD staff do not have decision-making authority or timely access to principal decision makers
- None of the review bodies are accountable for the impact of the changes they imposed

Progress Suffers

- Staffs allowed to assume de-facto program authority, stop progress and increase program scope
- Programs advance in spite of the oversight process rather than because of it
- PM does not have authority to bypass a stakeholders "no" vote, programs progress held hostage

Figure 2. Summary of DAPA Report Findings on Oversight
(extracted from Kadish et al., 2006)

Lastly, Ford, Colburn, and Morris (2012) found that large programs and budgets, such as acquisition category (ACAT) 1 multi-year programs, are easy targets for increased

oversight and longer approval chains. They showed a positive correlation between program size (measured by budget dollars) and the extent of oversight.

Factors Affecting the Level of Oversight

A factor affecting one's ability to manage oversight and stakeholders is political skill. Political skills include developing coalitions and gaining resources, assistance, and approvals from senior leaders and other relevant parties (Yukl, 2006). Additionally, De Wit (1988, p. 167) stated, "political skill will be a useful attribute on the part of the project manager to assure maximum satisfaction among the stakeholders. This is of special importance on public-sector projects." Furthermore, Yukl (2006) discusses five skills required for leading cross-functional teams (which includes integrated product teams [IPTs]). Specifically, political and interpersonal skills are associated with managing oversight and leading IPTs (Yukl, 2006). These skills involve understanding the needs and values of stakeholders to influence them and resolve conflict. In addition, a higher program classification can reduce oversight because it limits the number of people to those with the requisite security classification and need to know (Ford, Colburn, & Morris, 2012).

Finally, the literature on DoD acquisitions points to four main areas that affect oversight (Pagliano & O'Rourke, 2004; Kadish et al, 2006). The first factor affecting oversight is uncertainty. If all else is constant, the greater the program uncertainty, the more extensive the oversight will be. Second, oversight will increase as program criticality increases. In other words, if a program is critical to national security, a high degree of oversight will exist. Third, oversight will increase as trust decreases. If the chain of command and external stakeholders do not have a high degree of trust in what the program office is doing, more external reviews and proof will be required from the program office, thus leading to more extensive oversight. Finally, oversight will increase as the level of control and standardization from leaders increases. A model was developed (Figure 3) from the review showing how various factors affect the level of oversight in a program.

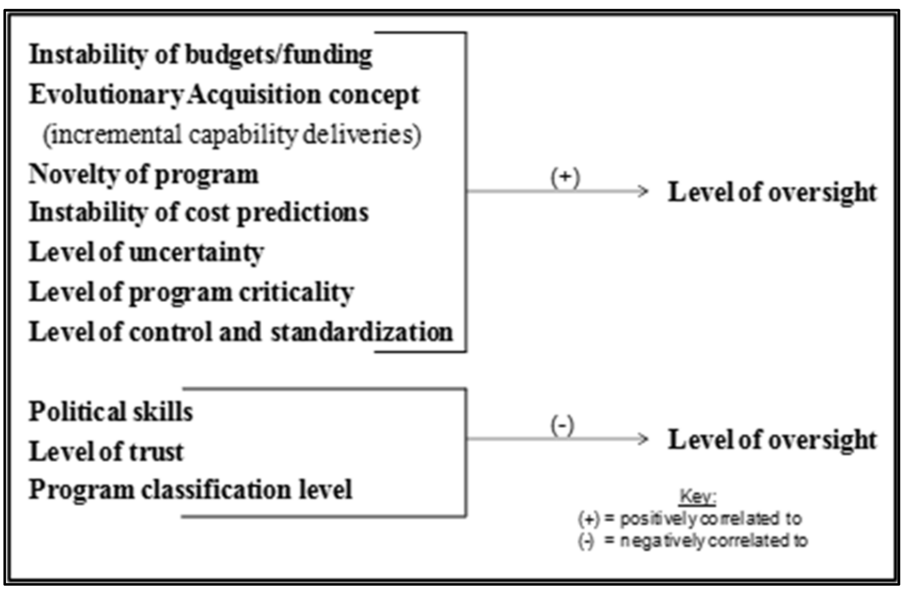

Figure 3. Factors Affecting Level of Oversight

Methodology

Research Design

Theoretical Method

This research utilized Grounded Theory Methods (GTM). Auerbach and Silverstein (2003) suggest GTM when a researcher's particular theory is at its early stage, not enough is known to state hypotheses prior to the investigation, and the major research involves identifying and categorizing elements to explore their connections. One of the key tenets of GTM is the iterative process of collecting, coding, and interpreting the data, also known as analytic induction (Binder & Edwards, 2010). As such, the interview process and data analysis were iterative in nature.

Sample Size

For the interview sample size, Eisenhardt (1989) states that 4–10 cases have worked well for most qualitative studies. Separate research conducted by Ellram (1996) identifies 6–10 cases as sufficiently large for evaluation and empirical grounding. Therefore, one-on-one interviews were conducted with 10 hand-picked senior acquisition leaders with diverse backgrounds and program experience.

Sampling Strategy

Eisenhardt (1989, p. 537) states that "random [case] selection is neither necessary, nor preferable" when building theory from case studies. Both purposive and snowball sampling were used in this research. Purposive sampling is used in qualitative research where individuals are selected based on their ability to better inform the researcher (Krathwohl, 1998; Patten, 2009). Snowball sampling entails identifying future participants based on recommendations from past participants (Krathwohl, 1998). In other words, the interviewees specifically suggest other people to interview. Snowball sampling successfully led to three interviews.

Personal Interviews

The population for this research consisted of Air Force program managers (PMs) with at least 20 years of experience. This included active duty and retired officers with ranks ranging from colonel to major general, active duty civilians with ranks ranging from GS-15 to Senior Executive Service (SES), and three government contractors. Both Air Force product centers, the Life Cycle Management Center (AFLCMC) and Space and Missile Systems Center (SMC), were represented, along with Special Operations Command (SOCOM). Programs covered included Global Positioning System (GPS), SOCOM Fixed Wing, Spacelift Range, Big Safari, F-22, Project Dragon Spear, Military Satellite Communications Directorate (MILSATCOM), FalconSAT, and the Secretary of the Air Force for Acquisition (SAF/AQ) and Aerospace organizations.

Coding: Atlas.ti

The ExpressScribe program was used to quickly transfer the interviews into Microsoft Word documents. The interviews were then coded, categorized, and analyzed in ATLAS.ti, a software program specifically designed for qualitative research, using an "open coding" of labels to extract major themes. All responses were analyzed for common themes. Three rounds of analysis were conducted in ATLAS.ti.

Survey

Additionally, a survey was developed from the interview data and distributed to the interviewees as well as junior officers and civilians in the introductory Fundamentals of Acquisition Management (FAM) 103 and mid-level Intermediate Program Management

(IPM) 301 skills courses. The survey contained 65 questions on a 1–5 Likert scale with an additional column for respondents to mark "unknown." Two classes from each course were surveyed. Fifty-eight students in the FAM 103 courses and 35 students in the IPM 301 courses provided usable surveys, totaling 93. The survey served three purposes:

1. Quantitatively validate interview responses with statistical significance
2. Prioritize themes from senior leaders
3. Identify knowledge gaps in the junior workforce

According to Cohen (1992), for an alpha (α) level of 0.05 (a 95% confidence level) and a medium effect size, one must have a sample size of at least 85. For a large effect size at the same confidence level, the sample size should be at least 28. Therefore, a conservative sample size of at least 85 was the goal; 93 usable student surveys were completed along with the additional 10 from the senior leaders.

Limitations/Assumptions

The nature of qualitative data and grounded theory research allows for interpretation depending on the researcher's point of view. Qualitative analysis "can therefore become biased based on individual experience and perspective" (Ford et al., 2012). The author endeavored to be cognizant of bias and avoid it when guiding interview discussions and interpreting, coding, and analyzing the data.

The results will have a high degree of reliability for all DoD program managers, even though the population set was limited to Air Force program managers. Studies have shown that all the Services are comparable with respect to their acquisition processes and record of success (Kadish et al., 2006; Burton, 1993).

Analysis and Results

Interview Analysis

From three iterative rounds of coding the data, four themes and 12 sub-elements emerged as shown in Figure 4.

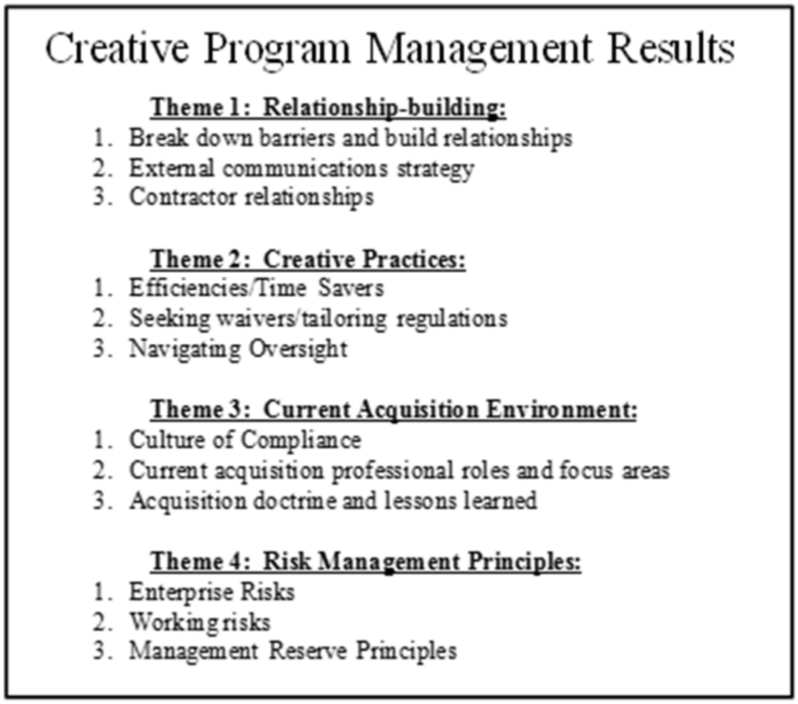

Figure 4. ATLAS.ti Round 3 Results

A co-occurrence table was developed analyzing where common occurrences within and between themes and codes occurred. The strength of a co-occurrence is affected by the number of times a comment was made either during a single interview or between several interviews. Strong and medium co-occurrences are collected and displayed in Table 1, with the three key findings for this paper highlighted.

Table 1. Strong and Medium Co-Occurrences Between Sub-Elements

Strong Co-occurrences		
Break down barriers & build relationships	strongly co-occurs with	External communications strategy
Break down barriers & build relationships	strongly co-occurs with	Navigating oversight
Medium Co-occurrences		
Break down barriers & build relationships	co-occurs with	Contractor relationships
Break down barriers & build relationships	co-occurs with	Seeking waivers/tailoring regulations
External communications strategy	co-occurs with	Efficiencies/time savers
External communications strategy	co-occurs with	Seeking waivers/tailoring regulations
External communications strategy	co-occurs with	Navigating oversight
Efficiencies/time savers	co-occurs with	Navigating oversight
Enterprise risks	co-occurs with	Working risks
Working risks	co-occurs with	Management reserve principles

The interviews were also categorized based on the respondents with experience as a program director (PD) and those with experience in rapid acquisitions. Five interviews were coded as those with PD experience and three interviews were coded as those with rapid acquisition experience. Figure 5 graphically displays the focus areas between the two

groups. Interestingly, the top three responses were the same for both groups. These were the External Communications Strategy, Break Down Barriers and Build Relationships, and Navigating Oversight. The main focus area for the program directors regarded their external communications strategies, which is understandable given the amount of oversight and number of stakeholders present in MDAP programs. A great deal of time is spent ensuring goals and strategies are being communicated clearly, accurately, and in a timely manner across organizational boundaries. Navigating Oversight was the second focus area for both program directors and those with rapid acquisition experience. However, a key difference exists between the two groups. Program directors' practices relating to oversight involved how to efficiently and effectively work through the current oversight and regulations. The oversight was viewed more as a fact of life that had to be worked through. In contrast, rapid acquisition responses focused more on how to circumvent the oversight from the start. In other words, rather than trying to efficiently work through oversight, rapid acquisition organizations delegate approvals and obtain waivers from the beginning (the thesis contains a case study on how USSOCOM instantly tailors 5000.02 via SOCOM Directive 70-1). Accepting the oversight level and figuring out how best to navigate it is very different than navigating oversight by avoiding the oversight from the beginning.

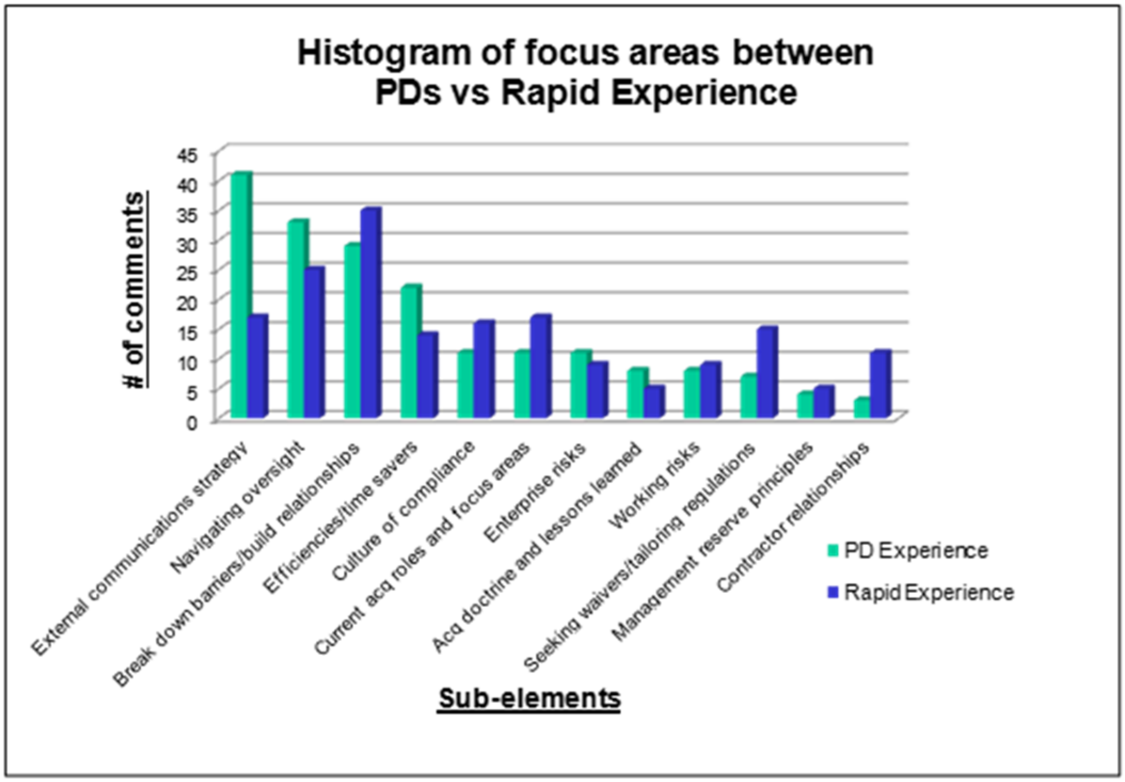

Figure 5. Histogram Comparing PD and Rapid Experience Responses

Additionally, a significant difference also existed between the PD and rapid experience responses for Seeking Waivers/Tailoring Regulations. Rapid acquisition organizations spend a lot of effort on tailoring programs and obtaining waivers. However, program directors often viewed the process of obtaining a waiver as more difficult than actually complying with the guidance, even if it did not make sense for the program. Therefore, program tailoring was a larger focus area for those with rapid acquisition experience. Figure 6 provides a decision-making process to obtain a waiver/tailoring based on the interviews in the "Seeking Waivers/Tailoring Regulations" sub-element.

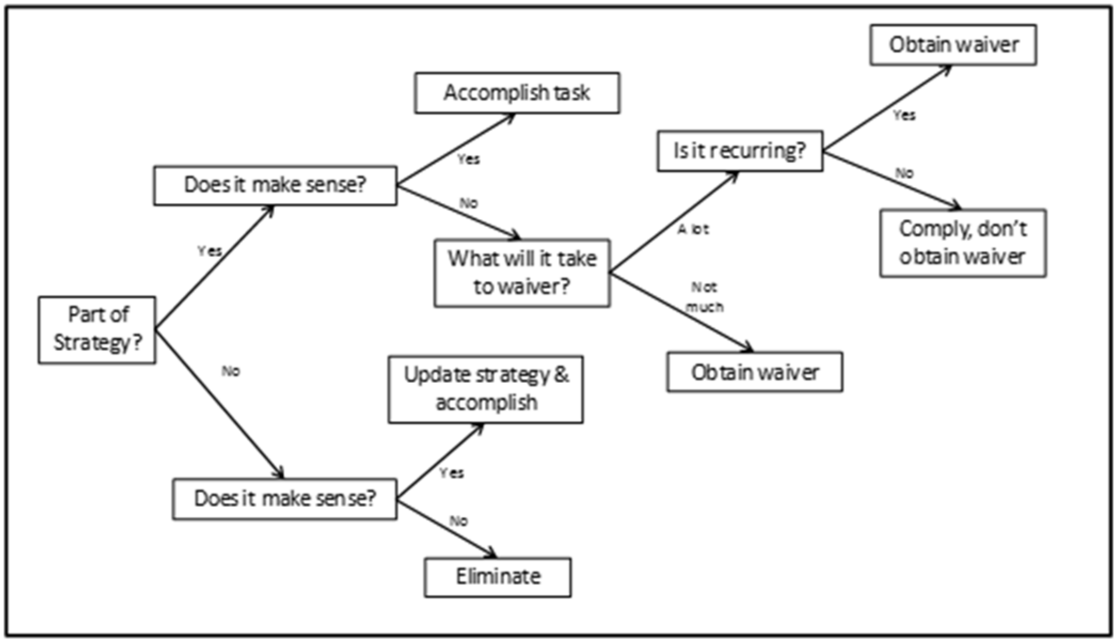

Figure 6. Decision-Making Process to Obtain a Waiver/Tailoring

Survey Analysis

Table 2 shows the overall survey data results divided into junior-level and senior-level responses. Of particular note for the results discussion is the percentage of "unknown" responses from students in each sub-element, some of which were unexpected.

Table 2. Overall Survey Results

Junior Responses				
	Mean	St. Dev	95% C.I.**	% Unknown
Break Down Barriers and Build Relationships	3.746	0.343	3.06-4.43	7.26%
External Communications Strategy	4.088	0.343	3.40-4.77	1.88%
Navigating Oversight	3.551	0.463	2.62-4.48	19.47%

Senior Responses				
	Mean	St. Dev	95% C.I.**	% Unknown
Break Down Barriers and Build Relationships	4.397	0.361	3.68-5	N/A
External Communications Strategy	4.500	0.082	4.34-4.66	N/A
Navigating Oversight	4.056	0.513	3.03-5	N/A

* Threw out Question #3 and #63 -- poorly worded/mis-leading

** Junior responses in 95% C.I. (Confidence Interval) range due to Empirical Rule (93 respondents)

** Senior responses in 95% C.I. range due to passing Shapiro-Wilk test of normality

An Analysis of Variance (ANOVA) was conducted for each sub-element. Both Break Down Barriers and Build Relationships and Navigating Oversight showed ANOVA significance at the 98% confidence level. Normality is required from both groups for a valid ANOVA test. Normality can be assumed for the students' responses because a random sample of 93 data points was collected and used (normality requires at least 30 data points

collected at random from the population; McClave, Benson, & Sincich, 2010). However, because only 10 data points were used for the senior leaders group, a Shapiro-Wilk test of normality was conducted on the three sub-elements with significant results. Navigating Oversight showed normality by having a Shapiro-Wilk value greater than 0.05. Initially, normality was not shown for the Break Down Barriers and Build Relationships sub-element, but after investigation one survey response was removed with high confidence that the respondent accidentally reverse coded one of the questions (answered 1 instead of 5 on the Likert scale) based on their interview remarks. After this was done, this sub-element passed the Shapiro-Wilk test, showing normality as well.

Overview of Theme and Sub-Element Results

The three key sub-elements were pulled from the results and are presented next. Figures 7–9 give an overall assessment for each sub-element. The overall assessment consists of two parts. A qualitative assessment rating of 1 to 5 is given based on the interviews and ATLAS.ti analysis (consistency and quantity of quotes, importance placed on quotes, number of co-occurrences, strength of co-occurrences, and other subjective measures). Additionally, quantitative top-level survey results are provided. The average response is on a 1 to 5 Likert scale from the survey, and the percent unknown is the percent of respondents that marked unknown for questions relating to each particular sub-element. Lastly, a "Yes" or "No" is given if the ANOVA test between the Junior and Senior responses for that sub-element was significant.

Theme 1 Sub-Element 1: Break Down Barriers and Build Relationships

Qualitative Assessment: 5

Survey Results:

	Junior:	Senior:
Avg response:	3.75	4.40
% Unknown:	7.3%	N/A
ANOVA Significant?		Yes

Figure 7. Overall Assessment for Theme 1 Sub-Element 1

- Building personal, trusting relationships requires consistency and stability
- Importance of following through on your word
- Importance of networking plus solid rationale
- Returning un-executable money builds trust in large programs

Building relationships and trust was the most commonly vocalized point throughout the interviews when discussing how best to navigate oversight or obtain a waiver or tailoring. Building and maintaining strong, trusting relationships with peers, co-workers, superiors, stakeholders, and various members of oversight is a continual process built over time. Trust is increased when project members follow through on their word. Although intuitive, the importance of doing what you say you will do, when you said you would do it, should not be undervalued.

Personal relationships with a high degree of trust require consistency and stability, which is often lacking in major acquisition programs. Air Force military PM tenure is typically a three-year tour for the actual materiel leader billet. Below the PM level, military acquisition

officers and engineers are usually in a program for two years and then do a permanent change of assignment (PCA) in which they switch jobs, which can be within the same program office or not. Even if military members prefer to stay in their assignments, it may not be good for their career to do so. The two years does not include any training, continuous learning, deployments, or additional duties the member might need to complete. One PM the author previously worked with stated the turnover issue clearly. Simply put, they lost half their people every summer, and that was a best case scenario. Worst case, they had a complete turnover one year in which no military continuity existed in a major ACAT I program. Stability and consistency, and the resultant trust and relationships, are constricted by the acquisition assignments process. Alternatively, organizations with a rich history and culture, such as Big Safari, with only three or four directors in the past 60 years, allow for close, personal relationships to be cultivated over time.

Networking is extremely vital to get one's issue "brought to the table." As one respondent mentioned, "I would have never been promoted once in my life if it wasn't about relationships …. I built relationships, I knew what people wanted, I knew the people to rely on, I did the extra thing, so relationship-building in that oversight process is instrumental." Networking builds trust by building closer relationships. This in turn increases the likelihood for a program approval, waiver, or tailoring. However, some negative aspects of networking were cited in the interviews as well. When one becomes more senior and is on their second or third tour at the same base, the people who have previously known them may still view them as their company grade officer (CGO) friend and not show the requisite respect. Additionally, past co-workers may not be as concerned about deadlines because they have a personal relationship with the senior. Last, the ease of recognizing "phony networking" was cited in a couple interviews, which is when one realizes someone is building a relationship solely for their own benefit. Although drawbacks to networking exist, the positive aspects far outweigh the drawbacks.

Building relationships is enabled by knowing what you are doing. Even if all the previous statements were true, if the rationale for what you are trying to do is flimsy, trust and networking will be far less effective. Having solid rationale in your decision-making is a key enabler to building trust because others may not want to enable members of their own network to assist in doing something that does not make sense if it will result in a lower trust level for them. As one respondent discussed, "Having a sense of purpose, knowing what you're trying to do, and having strong rationale communicates a message much better."

Lastly, returning un-executable money builds trust in large programs, if they are behind schedule and must do so. The money must be returned through the PEO, not directly to Air Force or other channels. Returning un-executable money does not include "expired" funds.

In this sub-element, the responses between the students and senior leaders were significantly different. The mean of the senior responses was 4.40 compared to a mean of 3.75 for students. As was briefed to each FAM and IPM class, the senior leaders emphasized and put much more value on relationship-building, building trust, and networking than did the students. The takeaway for the students is that as they are starting out or continuing their careers, they should begin building relationships with folks in required trainings, other programs, outside of work, etc., to expand their network. Of course, this cannot be done from a selfish or "further myself" point of view, but rather should be genuinely for the benefit of all.

In summary, as one respondent discussed, "What do I do to navigate [oversight]? I try to break down those barriers as much as possible. I really try to build relationships with

people, so that they know if something is really bugging them they can give me a call so we can talk back and forth."

Theme 1 Sub-Element 2: External Communications Strategy

Qualitative Assessment: 5

Survey Results:

	Junior:	Senior:
Avg response:	4.09	4.5
% Unknown:	1.9%	N/A
ANOVA Significant?		No

Figure 8. Overall Assessment for Theme 1 Sub-Element 2

- "Walking the building" every time
- Benefits of physical communications
- "Ground swell" or "burning your boots"
- Value of an elevator speech
- Knowing and communicating the "views of others"
- Ability to communicate across paradigms

Once a decision is made as to the strategy on an issue, how the PM externally communicates and "sells" what they're doing is very important. Several interviewees provided approaches they take. These include "walking the building" each time the PM is at the Pentagon, physical communications, and "ground swell" or "burning your boots" (proactive staff communication and dissemination of program strategies). Also, the value of an elevator speech, knowing the "views of others," and the ability to communicate across paradigms all go a long way toward effectively communicating what the program is trying to accomplish. Additionally, this sub-element had over a 2:1 ratio of responses from program directors versus respondents with rapid experience. In general, those with PD experience put much more emphasis into the importance and value of communicating what they are doing. The likely reason for this is because large ACAT I programs experience much more oversight (due to the multi-year, high-dollar value, and industry and congressional stakeholders) than smaller, more rapid programs. However, in ACAT I programs, decision-making and oversight require more stakeholder analysis and often consist of a "one-shot" opportunity to obtain program approvals, thus leading to the higher importance of the program's external communications strategy from program directors.

Several respondents mentioned how they "walk the building" when they are visiting Washington, DC. This term is used to describe how a PM should visit key stakeholders, members of oversight, and members of their network when walking around the Pentagon. In particular, they should do this each time they are there, especially when nothing is needed from the people they are visiting. Visiting offices and asking folks if they need anything from you helps build trust and, with noble intent all along, can enable reciprocal generosity when you need something from them. In other words, a genuine, proactive offer to help others without any expectation for them to reciprocate in the future is an effective communication strategy to build long-term relationships.

Additionally, physical communications are far better than electronic means. Physical communications enable one to match a face with a name, increase the importance of the issue (if one flies to discuss an issue rather than e-mailing or calling, they are putting higher importance on the issue), and make it more difficult to ignore the issue. Ignoring an e-mail is fairly easy and ignoring a phone call is not much harder. However, when someone physically visits you to discuss an issue, and then comes back to discuss the results, it is far more difficult to ignore that person's requests.

Another way to externally communicate a strategy is by "ground swell" or "burning your boots." This refers to the program staff, predominantly the Program Element Monitor (PEM), proactively communicating and disseminating the strategy and goals throughout the myriad program stakeholders in Washington, DC. This is done by working the staffing and issues from the ground up, communicating to all stakeholders and staffs first so that there are no surprises and so that any possible issues are brought to light early on. As one respondent mentioned, "really good action officer work can save hours upon hours of wasted time in meetings."

Business, organizational behavior, and management books often discuss the importance of an elevator speech (albeit using different terms). The premise is that if you were to find yourself riding in an elevator with a senior manager, you should always have a short (~1–2 minute) speech or talking points in mind to gain the senior manager's support in the time it takes to ride in the elevator. Interviewees discussed the importance of this concept in acquisitions as well, with some discussing the value of a hard-hitting one-liner. PMs need to have a short, direct, and effective means to communicate the program capability and its vital importance without going into highly technical or programmatic details. As one respondent said, "When I was having a problem getting funding for xx program, I met with a key staffer. I said to him 'Do you want our enemies to be able to launch a nuke at us and we're not able to detect it early enough to destroy it?"' 'Well, no.' 'This program ensures early warning to protect the homeland. Period.'" These statements should be clear and concise to the maximum extent possible. An excellent one-liner can be crucial for three reasons:

1. if one unexpectedly has a moment of the senior's time;
2. to translate a technical program into a tangible, national security issue; and
3. in helping the oversight help the program.

Staff Summary Sheets (SSS) have a section in which the "views of others" can be documented. The purpose is to provide any differing views amongst various stakeholders, specifically influential stakeholders, when staffing a package. Bringing contentious viewpoints to the table early in the process has several benefits. It allows you to

1. take the time to grasp the heart of an issue and what you want to transmit,
2. clearly articulate your position, and
3. clearly articulate the views of others.

Once this is done, the package gets sent up the chain. The structure of an SSS allows for clear communications on paper rather than dealing with the myriad information, or often mis-information (as one respondent discussed), that goes through e-mail. Additionally, "if you don't accept or work those views of others from the get go, by the time you end up briefing your leadership, and then your leadership's leadership, you end up entrenched in a position and you end up entrenched so much that it's hard to walk backwards from anymore. So it removes your flexibility from a compromise or otherwise." Although it often works out

in the end, it can be quite painful to go back several layers in the staffing process and the resultant coordination change when a relatively small or easy change could have been accomplished, provided it was worked up front.

When discussing how best to communicate or “sell” an issue, it is very important to communicate across paradigms. Providing information in a way that program managers, users, budgeters, engineers, and senior leaders in oversight all understand will help prevent confusion and delays, particularly in the staffing process. Similar to knowing your audience when giving a briefing, generally it is beneficial for a PM to know the audience for each particular briefing, meeting, and document and tailor the product to the audience. A briefing inundated with technical jargon and specifications is probably not best when providing program status to the user or a senior leader.

Theme 2 Sub-Element 3: Navigating Oversight

Qualitative Assessment: 5

Survey Results:

	Junior:	Senior:
Avg response:	3.55	4.06
% Unknown:	19.5%	N/A
ANOVA Significant?		Yes

Figure 9. Overall Assessment for Theme 2 Sub-Element 3

- Pick and choose battles while preventing “blood in the water”
- Acquisition oversight lacks government PM experience
- Reduce oversight by executing the plan
- Smartly defend program budgets

This sub-element discusses creative practices in working with oversight. Current oversight also has several shortcomings. To be expected, senior leaders had a significant difference in responses to the importance of navigating oversight than did students. Seniors placed more emphasis on how to creatively navigate oversight, especially the subset of senior leaders with program director experience.

First, acquisition experience is lacking in acquisition oversight positions. Political appointees often come from industry, but as one respondent commented, “I’ve been to all the schools you’re supposed to, and they always talk about how industry does things. Industry and government are simply very different, and the same approaches will not work for both.” Respondents also noted that the inexperience results in a lack of urgency. Techniques to work with inexperienced oversight include clearly making your case for what you are doing and laying out when a decision must be made (and the rationale and outcomes if a decision is not made by then). If this does not work, allies either up the chain or in other oversight positions must be gained to defend and promote your position. An operations advocate at the MAJCOM or HQ level was cited as an extremely beneficial/influential ally. Operations advocates will defend the program’s requirements, criticality, and need as the user, rather than the program office defending its own jobs.

Also, one way to reduce program oversight is to reduce the ACAT level of the program whenever possible. For example, ten $100 million programs have much fewer reporting requirements than one $1 billion program. This will allow each program to be smaller and leaner, and have less oversight (all else held equal). One ACAT 1D program noted how the documentation requirements for a milestone review have become debilitating—96 documents containing 12,000+ pages. As the literature review showed, increasing a program's classification level reduces oversight as well. However, both a program's classification and ACAT level are determined by either law (for the ACAT level) or strict policies (classification level); therefore, a PM has little authority to change these after program conception.

When navigating oversight, PMs must pick and choose their battles on the few issues on which they are not willing to compromise. This will reinforce to the community what is not negotiable from the PM's point of view. Correlated to this, one must prevent "blood in the water" during decision reviews. This refers to a stakeholder or staff member attacking controversial issues of the program during a meeting. The PM must directly and convincingly quell these arguments so that other stakeholders do not latch on, much like sharks when there's blood in the water. For example, if a stakeholder questions the reasoning for the contract type in the acquisition strategy, the PM should then and there explain why it is the best contract type and incentive structure for the program. A hesitant answer or having to get back to the stakeholder later allows for other stakeholders to look into the issue and lose confidence in the PM having the requisite control and understanding of the program. Of course, this needs to be tempered with difficult, unforeseen questions that do not have a known answer. In these (hopefully rare) cases, a PM should promise to get back to the person as quickly as possible. In summary, keeping the "blood out of the water" can be immensely beneficial.

Practices in which programs defend their budgets (with integrity) reduce program oversight as well. The best way to defend against budget cuts and reduce intervention is simply to stay green—obligate and expend money on time. Second, programs should make every effort to fund disconnects internally, as no one ever wants to ask for more money (nor is it currently available). The 19.5% unknown responses from students in this sub-element arise predominantly from this survey question. Surprisingly, 40% of students did not know if programs should fund disconnects internally to the maximum extent possible. Therefore, it is recommended that the appropriate continuing education course expand the teaching on how PMs can avoid program interference by smartly managing funds internally. Although this is of particular value to program directors, PMs at all levels can still learn from this heuristic and do what they can to manage funds allowing for some degree of flexibility. Third, perceptions are worse than reality in many areas of government acquisitions. If a program is perceived to be fat (over-funded) or behind schedule, whether it is true or not, the program is a more apt candidate for cuts.

Also, when hiring a material leader, some programs may find it highly beneficial to hire one with recent PEM experience. For example, a pre-Milestone B program (even though it is not technically called a program yet) will experience numerous decision reviews, staffing, and oversight during the Milestone B and source selection processes. Recent PEM experience greatly increases the process familiarity and likelihood that recent relationships will prove useful in working the system.

Conclusions

In review, the predominant finding of this research is that senior acquisition professionals believe that relationships and building trust are of paramount importance. A high correlation exists between three main sub-elements: Break Down Barriers and Build

Relationships, External Communications Strategy, and Navigating Oversight. The first two are vital to effectively and efficiently navigating oversight. Both program directors and respondents with rapid experience chose these three sub-elements as their top three responses.

For Navigating Oversight, program directors more often accepted the level of oversight as a fact of life, so they work hard to efficiently work with and through the oversight for program success. However, rapid acquisition organizations navigated the oversight process by delegating approval authorities and tailoring programs from the start, thus avoiding a degree of oversight from the beginning.

Additionally, junior personnel did not believe the relationships nor the oversight aspects to be as important as the senior leaders judged. Therefore, an opportunity exists for DAU or AFIT classes to bolster the material relating to these topics. This is especially important not only because the senior leaders attribute success to these areas, but because relationships can be built over a career and the process of building relationships can begin at the start of one's acquisition journey.

Recommendations for Future Research

The following are recommendations for future research. Future research can be accomplished to investigate the root cause of the significant differences shown between introductory, mid-level, and senior acquisition professionals, both for differences in the Likert scale responses and for questions with a significant number of "unknown" responses. Additionally, the same thesis methodology could be applied to industry program managers to assess the external validity of this research to industry.

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The RITE Approach to Agile Acquisition

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Abstract

As directed by the National Defense Authorization Act (NDAA) of 2010, Public Law 111-84, the defense acquisition community is transitioning in an effort to adopt software best practices for delivering information technology in an incremental and iterative model. The Deputy Secretary of Defense provided a report to Congress titled *A New Approach for Delivering Information Technology Capabilities in the DoD,* delineating the overarching framework to reform the acquisition of information technology to better address and fulfill warfighter requirements. Many governmental agencies, anticipating future directives, are implementing Agile software development methodologies and demonstrating success using these methodologies on DoD-sponsored programs. As an example of this, the Rapid Integration and Test Environment (RITE) established by SSC Pacific in 2008 provides a standardized Agile development environment for its C2 programs. Much of the work to date has addressed program items controlled at lower command levels while awaiting restructuring of the acquisition milestone and review requirements specified in DoDI 5000.02. This report presents the research completed in analyzing traditional acquisition program milestone reviews and documentation requirements and identifies streamlining opportunities that support Agile development. The report also validates the RITE initiative in providing the structured engineering approach that makes Agile development viable in a DoD acquisition environment.

Introduction

The National Defense Authorization Act (NDAA) for Fiscal Year 2010, Public Law 111-84, Section 804—hereafter referred to as Sec. 804, 2010 NDAA—established the requirement for the Department of Defense (DoD) to streamline the acquisition of

information technology. In response to that request, the Office of the Deputy Secretary of Defense (2010) provided a report titled *A New Approach for Delivering Information Technology Capabilities in the DoD.* This report created the overarching framework to reform the acquisition of information technology to better address and fulfill warfighter requirements. While this new requirement established the basics for streamlining information technology acquisition, it did little to provide meaningful, actionable practices that an acquisition program can execute. The goal of this research was to identify opportunities to create actionable Agile processes that information technology programs can use to execute streamlined programs.

Background

The Sec. 804, 2010 NDAA requirement established the parameters for the new acquisition process based on the March 2009 report of the Defense Science Board (DSB) Task Force titled *Department of Defense Policies and Procedures for the Acquisition of Information Technology*. The report was required to include several characteristics that Congress determined necessary for successful implementation:

1. early and continual involvement of the user;
2. multiple, rapidly executed increments or releases of capability;
3. early, successive prototyping to support an evolutionary approach; and
4. a modular, open-systems approach. (NDAA for Fiscal Year 2010, 2009)

These characteristics are significant in that they also describe the elements indicative of an Agile development methodology.

In response to Sec. 804, 2010 NDAA, the DoD provided a report to Congress highlighting its plans to reinvent the IT acquisition process. Noting the departure necessary from a traditional acquisition process, the DoD provided the following:

> Acquisition activities in the new process for delivering IT capability will differ significantly from the traditional weapon system development acquisition process and will be separately defined in DoD IT acquisition policy issuances. The IT acquisition process will be agile to respond to a dynamic technology environment and to address unique challenges, such as cyber threats (Office of the Deputy Secretary of Defense, 2010, p. 9).

As shown in the next section, this approach provides a flexible structure dedicated to positive, customer-driven outcomes.

Agile Development

Agile development focuses on close customer interaction and rapid, iterative, and incremental development cycles that produce a working product. This approach focuses on early feedback and flexibility adapting to customer needs.

In describing Agile methods, Lapham et al. (2011) noted that the concepts and practices associated with Agile development arose out of the Agile Alliance. In an effort to identify an alternative to elaborate and time-consuming software development processes, the Agile Alliance created a set of values that focus on people, collaboration, and development of quality software products for their customers (Lapham et al., 2011, p. 1).

The Agile Alliance's efforts resulted in the Agile Manifesto for Agile Software Development:

> We are uncovering better ways of developing software by doing it and helping others do it. Through this work we have come to value:

> **Individuals and interactions** over processes and tools
> **Working software** over comprehensive documentation
> **Customer collaboration** over contract negotiation
> **Responding to change** over following a plan
>
> That is, while there is value in the items on the right, we value the items on the left more. (Lapham et al., 2011, p. 1)[1]

Critics of Agile development cite documentation reduction as problematic in development efforts, but these concerns are discounted by seasoned developers. In Agile development, the amount of documentation is determined by the software, not the desire of the developer. It is essential to understand that while documentation is important, it should not act as a replacement for communication and collaboration. Regarding Agile development's approach to documentation, Lapham, Williams, Hammons, Burton, and Schenker (2010) observed, "The Agile community would argue instead that documentation is important, but no more documentation should be created than is absolutely necessary to support the development itself and future sustainment activities" (p. 4). Documentation developed using the Agile methodology can support the intent and objectives of the documentation requirements of the DoD acquisition process.

Agile development is not the only initiative working to streamline and improve the effectiveness of development activities. The Space and Naval Warfare Systems Command (SPAWAR) Rapid Integration and Test Environment (RITE) initiative focused their efforts on key areas in the development cycle that work collectively to shorten cycle-time and improve the efficiency of the development effort.

Rapid Integration and Test Environment

In 2008, the Program Executive Office (PEO) Command, Control, Communications, Computers, and Intelligence (C4I), Command and Control Program Office (PMW 150) began implementation of the RITE initiative. This initiative was born out of necessity in that the existing process for requirements definition and management, as well as processes for software development, did not consistently deliver high-quality Navy Command and Control (C^2) systems either on time or within budget.

The RITE initiative, as implemented, represents a new life cycle model for Navy C^2 software that meets many of the process objectives identified in Sec. 804, 2010 NDAA and improves efficiencies in Navy C^2 application development. RITE places increased emphasis on early and frequent customer interaction and software testing, as well as necessary software engineering practices at the source code level. RITE is a structured approach to software development, taking full advantage of technology advances and open-source models to automate processes and shorten development cycles—thereby increasing the maintainability of the software baselines. The new automated processes also allow a reduction in low-value-added processes and manually developed reports, further streamlining the acquisition cycle and improving efficiencies. The initiative clarifies software delivery requirements, adds additional engineering rigor to deliverables, and reduces the opportunity for misunderstanding between end users and developers. Lastly, RITE uses a centralized information repository that allows all stakeholders to communicate, coordinate, and collaborate virtually.

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[1] The Manifesto for Agile Development was created during a meeting of representatives from across the nascent Agile community and included the following: Kent Beck, Mike Beedle, Arie van Bennekum, Alistair Cockburn, Ward Cunningham, Martin Fowler, James Grenning, Jim Highsmith, Andrew Hunt, Ron Jeffries, Jon Kern, Brian Marick, Robert C. Martin, Steve Mellor, Ken Schwaber, Jeff Sutherland, and Dave Thomas.

As RITE has evolved and process improvements have been realized, additional uses for RITE in support of the C^2 life cycle have been identified. This support includes facilitating close collaboration with outside agencies to ensure that the development knowledge and test and evaluation (T&E) results are shared in order to reduce overall project time. Figure 1 shows the RITE processes as they align with all four phases of the new IT acquisition life cycle. The arrows indicate areas where RITE (consisting of people, processes, and infrastructure) directly supports the acquisition of Navy C^2 capabilities and systems.

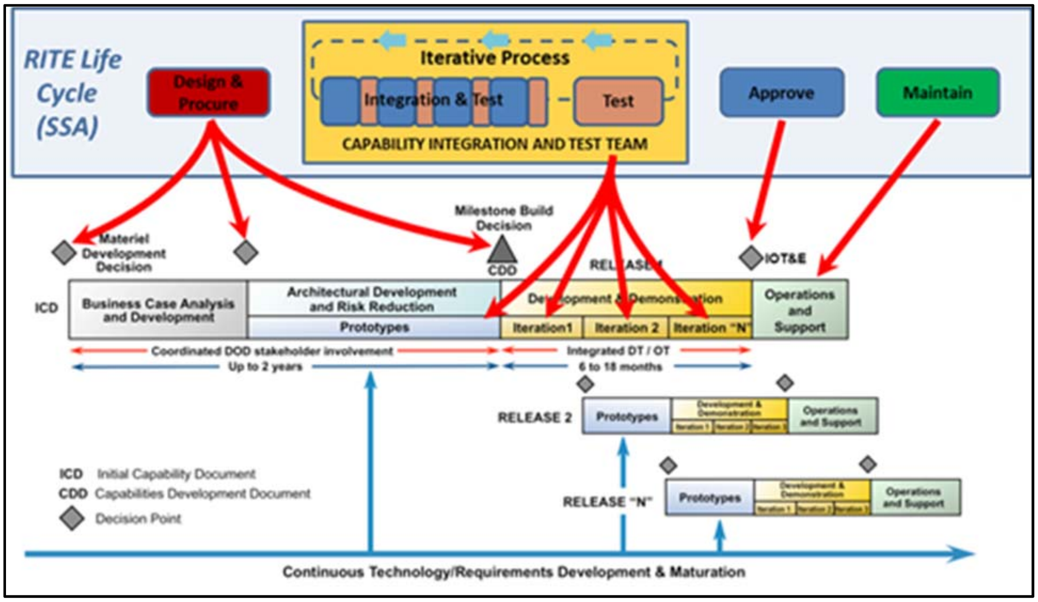


Figure 1. RITE Alignment With 2010 IT Acquisition Changes

Defense Acquisition Management System

The Defense Acquisition Management System (see Figure 2) is the management process guiding all DoD acquisition programs. The initiating directive, DoD Directive (DoDD) 5000.01, provides the policies and principles that govern the defense acquisition system, and DoD Instruction (DoDI) 5000.02, Operation of the Defense Acquisition System, provides the management framework that implements these policies and principles. “The Defense Acquisition Management Framework provides an event-based process where acquisition programs progress through a series of milestones associated with significant program phases” (DoD, 2012).

The Defense Acquisition Management System is used throughout the DoD as the single overarching methodology for acquiring business and weapons systems.

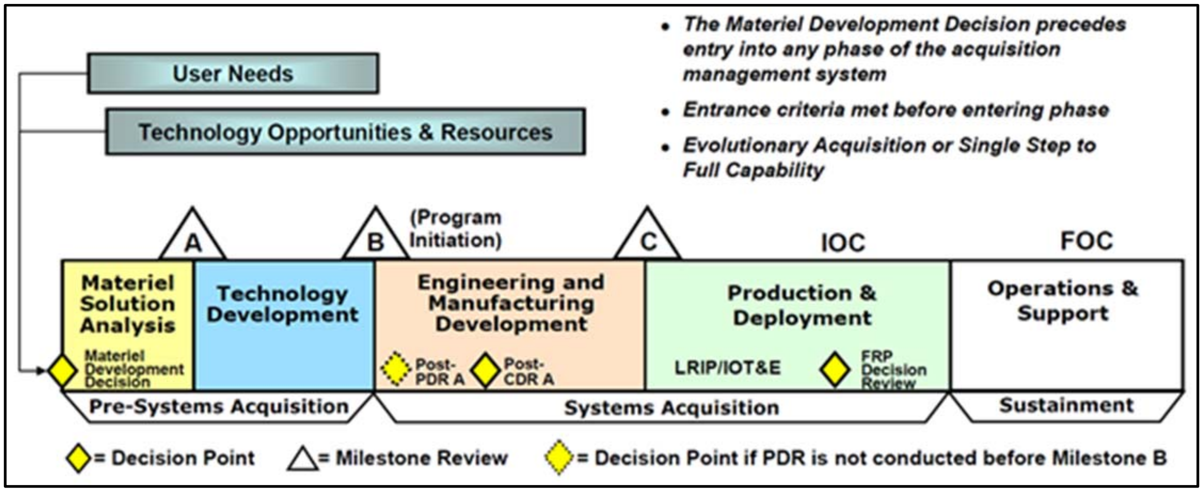


Figure 2. The Defense Acquisition Management System

Related Research

Defense Science Board Task Force Report on Department of Defense Policies and Procedures for the Acquisition of Information Technology

In March 2009, the DSB Task Force reported on the evaluation of the acquisition of information technology (IT) within the DoD. This report identified critical problems with the management of IT acquisitions using an enterprise approach resulting in a "profound operational impact" (DSB Task Force, 2009, p. 1). The report identified problems in responsiveness and the ability to address operational needs. Citing a 2006 DSB study titled *Information Management for Net Centric Operations*, the report noted,

> Especially important, according to the 2006 report, was that much of the military capability used to support the conflicts was paid with supplemental funding—programs that were not part of the Department's planned capability. This circumstance reflects the fact that the need for such programs could not be predicted during previous core program and budget planning, and the system was not sufficiently agile to react once the need was apparent. (DSB Task Force, 2009, pp. 1–2)

The report goes on to identify the evolution of weapons system software reliance in the 1970s at 20% to as much as 80% in 2000. This is a critical issue in light of the reduction in U.S. computing graduates and qualified expert government staff and increased reliance on IT at a time of rising vulnerabilities and threats (see Figure 3; DSB Task Force, 2009, p. 6).

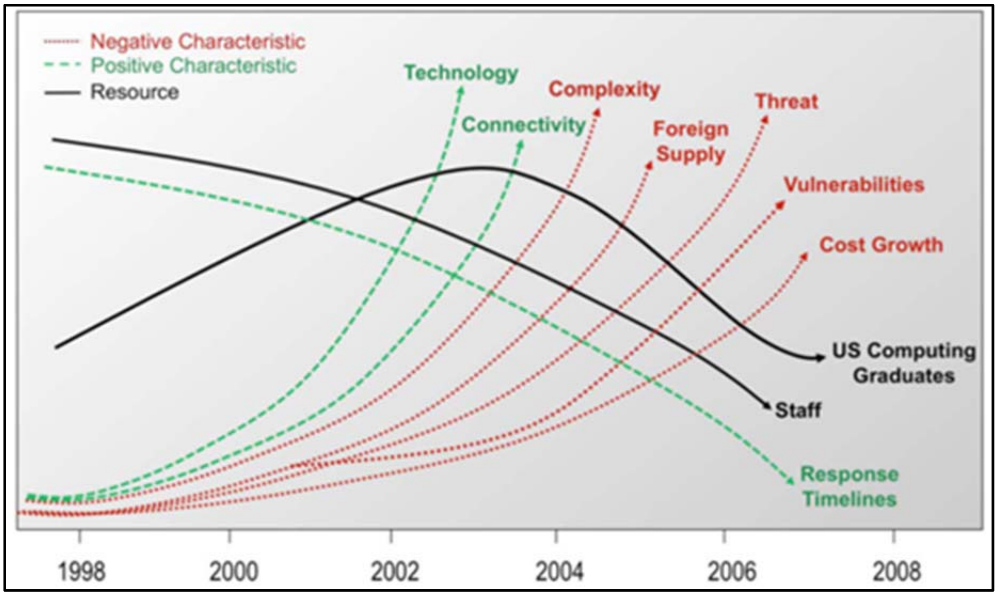


Figure 3. The Perfect IT Storm
(DSB Task Force, 2009)

The DSB Task Force's findings identified the need for a unique acquisition process for IT. Commenting on the failure of major defense systems, the task force also identified the need to shorten the lengthy acquisition process and to provide the flexibilities necessary to support continuous changes and upgrades. Other critical elements of change identified by the DSB Task Force include the need to align acquisition authorities and organizational structure under the Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics (OUSD[AT&L]) to better manage the technical aspects of IT acquisitions and the need to consider proven experience as an added component in evaluating the education and certification of members of the acquisition workforce.

Considerations for Using Agile in DoD Acquisition (Carnegie Mellon University, Software Engineering Institute)

This document was created to provide additional information on Agile development as it relates to DoD acquisitions, references actual DoD programs that have benefited from the adoption of Agile practices within their respective programs, and includes analysis of relevant literature regarding Agile development. Lapham et al. (2010) answered many questions regarding Agile development, but they specifically answered whether Agile development methods are able to produce better products within cost and schedule requirements (yes) and addressed the barriers which inhibit the DoD's adoption of Agile development methods.

In determining the barriers to DoD's Agile development adoption, Lapham et al. (2010) noted,

> The barriers to adopting Agile in the DoD appear to be primarily cultural. That is to say that there is little in the way of regulation or guidance provided in DoDI 5000.02 that would prevent the use of Agile. This instruction does impose specific constraints on the acquisition office, but these constraints would be true of any development environment. (p. 27)

While not finding any primary barriers within the DoDI 5000.02, Lapham et al. (2010) did address issues with the Federal Acquisition Regulation, citing the need to address

contracting requirements to support Agile development. These changes would require the accommodation of Agile as part of a system's acquisition strategy at the beginning of a program development effort (Lapham et al., 2010, p. 27). The authors also pointed to significant concerns regarding milestone reviews within the DoD acquisition system:

> A very specific acquisition issue and sticking point is that Agile methodology does not accommodate large capstone events such as Critical Design Review (CDR), which is usually a major, multi-day event with many smaller technical meetings leading up to it. This approach requires a great deal of documentation and many technical reviews by the contractor. (Lapham et al., 2010, p. 13)

In addressing the primary questions raised regarding Agile development and its use within the DoD, Lapham et al. (2010) noted that end-user participation and culture are issues that must be addressed before using Agile methods within a program (p. 44).

Agile Methods: Selected DoD Management and Acquisition Concerns (Carnegie Mellon University, Software Engineering Institute)

This document is the second in a series regarding Agile development methods and the use of Agile within the DoD. While focusing on a better understanding of Agile development as it pertains to the DoD acquisition system, Lapham et al. (2011) targeted this report to address Agile development implementation approaches for acquisition and development personnel (p. 2).

Lapham et al. (2011) provided thorough discussions of Agile development, why Agile methods are increasing within the DoD, contracting requirements for implementation within Agile programs, and the use of change management within an organization, specifically applicable to a program management office (PMO), to implement Agile methods. Most applicable to the analysis within this paper is the discussion of milestone reviews within systems development and its effect on Agile development. (Lapham et al., 2011, pp. 10–11). The authors provided a thorough evaluation of milestone reviews, including the effort required to produce the supporting documentation and not the challenges associated with adapting a program's milestone reviews to an Agile methodology:

> The intent of any technical milestone review is for evaluation of progress and/or technical solution. For PMOs trained and experienced in the traditional acquisition methods, evaluating program progress and technical solutions follows well established guidelines and regulations. Very specific documentation is produced to provide the data required to meet the intent of the technical review as called out in the program specific Contract Data Requirements List (CDRL). The content of these documents and the entry and exit criteria for each review is well documented. However, even in traditional acquisitions (using traditional methods), these documents, exit and entry criteria can be and usually are tailored for the specific program. Since the documentation output from Agile methods appears to be "light" in comparison to traditional programs, the tailoring aspects take on additional aspects. Some of the specific challenges for Agile adoption that we observed during our interviews that must be addressed are as follows:
>
> - incentives to collaborate,
> - shared understanding of definitions/key concepts,
> - document content—the look and feel may be different but the intent is the same—and

- regulatory language. (Lapham et al., 2011, pp. 38–39)

Analytical Approach

The analytical approach involved exhaustive analysis of technical reviews and documentation to identify possible areas in which duplication or overlap currently exists within the review structure or the documentation set required when developing a product.

The review included a thorough analysis of all milestone reviews and documentation associated with a typical development effort. The analysis examined the technical definition of each review, the statutory or regulatory requirement upon which it is based, the program participant/organization responsible for execution of the review, the program participant/organization responsible for conducting the review/completing the document (subordinate organization—typically Software Support Activity [SSA], In-service Engineering Agent [ISEA], etc.), key team members involved, entrance and exit criteria for the review, recipient of the completed review results (PEO, Milestone Decision Authority [MDA], etc.), any other stakeholders, and previous and next process flow steps. The review process was refined to focus on the following milestone reviews: Preliminary Design Review (PDR), Critical Design Review (CDR), Test Readiness Review (TRR), System Verification Review (SVR), and Production Readiness Review (PRR), which were evaluated against Agile development requirements. Further analysis was conducted against the DoD and SPAWAR Systems Command (SPAWARSYSCOM) System Engineering Technical Review (SETR) PDR and CDR Risk Assessment Checklists to provide a cross-referenced analysis against PDR and CDR requirements. These checklists were targeted due to their complexity (The DoD PDR checklist is 860 line items, and the DoD CDR checklist is 929 line items) and their applicability within development timelines associated with Agile development. Although SPAWARSYSCOM SETR checklists for PDR/CDR closely follow the DoD checklists (with 871 and 906 line items, respectively), the difference in line items represents tailoring to address Navy specific requirements.

The documentation analysis included an evaluation of which milestones within the defense acquisition system required completion or updating of each specific document. Additionally, the evaluation included the review of the documentation set required by the SPAWARSYSCOM SETR Risk Assessment Checklists.

Results

This section highlights the pertinent analysis of the reviews and documentation information collected during the preliminary part of this effort. Discussions with experienced program professionals and other acquisition workforce personnel also occurred during the data collection and analysis phases to better inform the group's decision-making process.

Of note, during the analytical phase of this effort, discussions regarding the role of the cognizant technical authority (TA) and their impact (positively or negatively) on the viability of the development effort. According to the Naval Warfare Systems Certification Policy, a TA's role within an organization is as follows:

> The entity with the authority, responsibility, accountability, and technical integrity to establish, monitor, and approve technical standards, tools, and processes in compliance with applicable DoD and DoN policy, requirements, architectures, and standards. (DoN, 2012, pp. B–6)

While the TA's role is focused on institutional level technical compliance, the TA's role remains secondary to the program manager's (PM's) and MDA's role in validating and approving the planned milestone review and programmatic documentation streamlining efforts. Even so, the TA's role as the technical advocate in support of development methods

such as Agile cannot be overstated. A TA's commitment (and through extension, a command's commitment) to Agile development can be helpful in supporting the MDA's decision to approve a PM's request to eliminate or otherwise minimize documentation requirements.

Primary Review Analysis

The initial analysis of technical reviews included the following: Initial Technical Review (ITR), Alternative System Review (ASR), Integrated Baseline Review (IBR), System Requirements Review (SRR) ,Technology Readiness Assessment (TRA), System Functional Review (SFR), PDR, CDR, TRR, SVR, Functional Configuration Audit (FCA), PRR, Operational Test Readiness Review (OTRR), Physical Configuration Audit (PCA), Integration Readiness Review (IRR), In Service Review (ISR), Development Test Readiness Review (DTRR), and Operational Test Readiness Review (OTRR). Although this analysis was an essential first step and helped to visualize individual reviews within the context of the DoD Acquisition Management System (see Figure 4), no major streamlining opportunities were identified in the analysis.

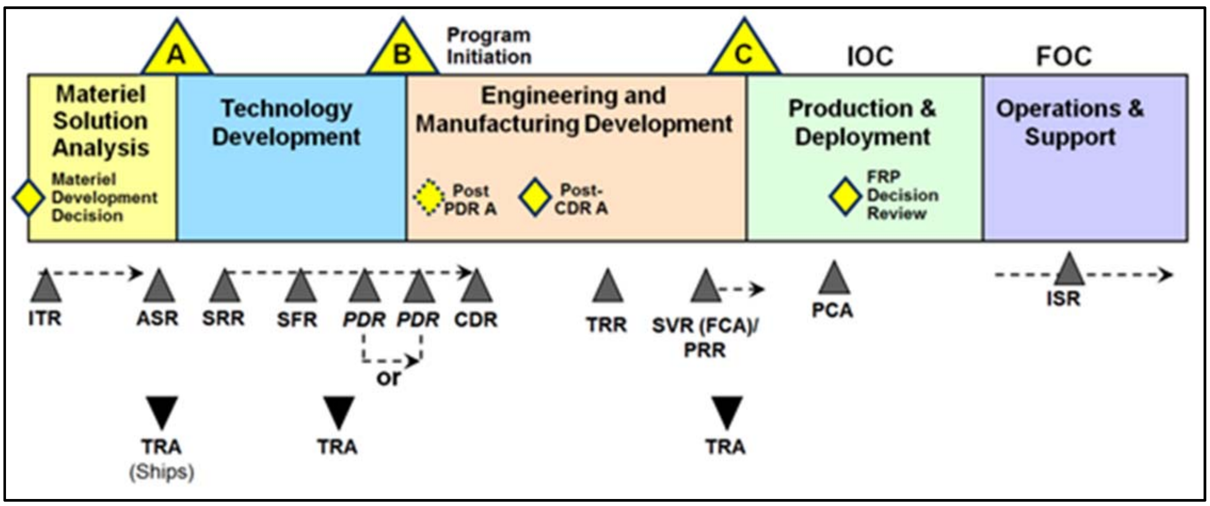


Figure 4. System Engineering Technical Reviews According to the DoD Acquisition Management System

In evaluating the reviews against Agile development principles, it was evident that to achieve any streamlining within the review process, the numerous review requirements would need to be downsized and re-envisioned to address the primary elements of the existing reviews. This was preliminarily documented in the DSB Task Force's (2009) report *Department of Defense Policies and Procedures for the Acquisition of Information Technology* (see Figure 5). The DSB Task Force's (2009) recommendation streamlined the milestone review process to eliminate the complex, all-encompassing milestone reviews in favor of more frequent, tailored decision points that enable a program to identify problems earlier, which results in more "robust and maintainable designs" (pp. 52–53).

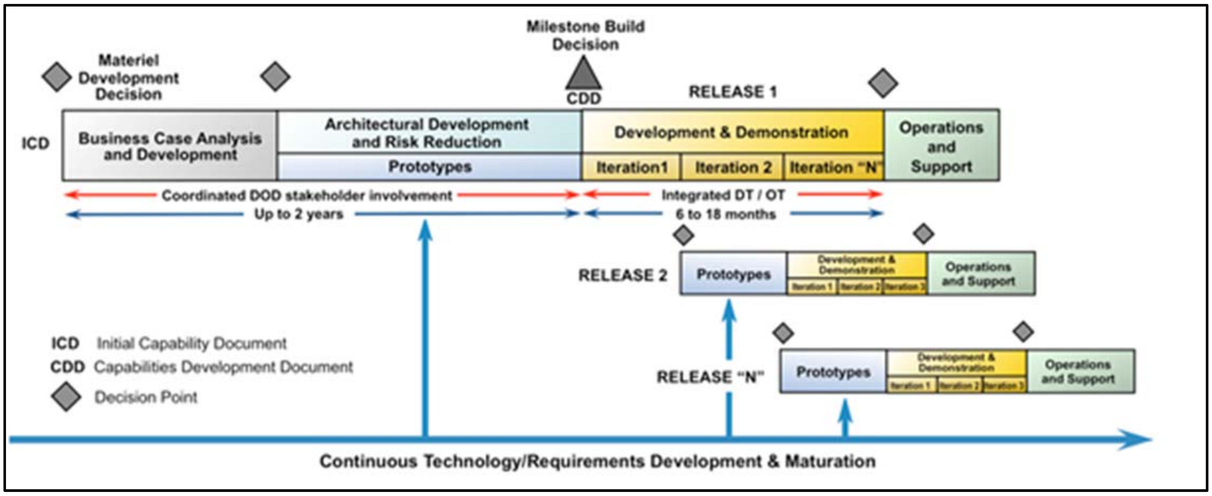
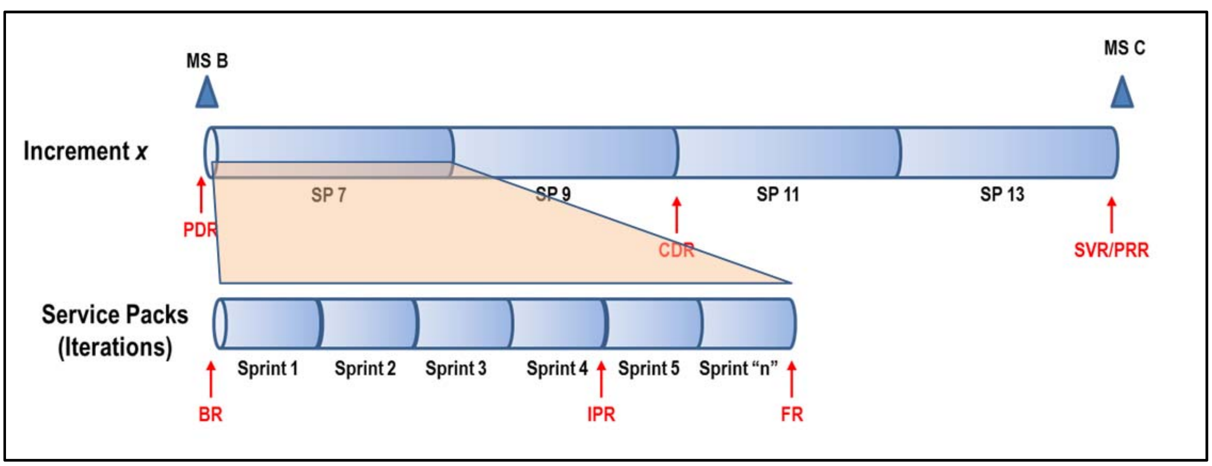


Figure 5. New Acquisition Process for Information Technology
(DSB Task Force, 2009, p. 48)

In the context of the primary milestone reviews (PDR, CDR, and SVR/PRR), a nominal Agile development structure was created (see Figure 6), providing increment releases (two-year cycles) that include service packs (six-month cycles of completed development efforts that have the potential to be forwarded as release candidates). Within each service pack is a series of sprints, which represent a standard form of Agile development. This construct allows the identification of a Build Review (BR; reviews are shown in red in Figure 6) at the beginning of each service pack, which addresses elements of the increment level PDR and subsequent CDR; an Interim Progress Review (IPR) at Sprint 3 or 4 to assess progress regarding cost, schedule, and performance and evaluate the service pack functional backlog compared to the current backlog, validating the detailed design of the remaining sprints; and a Fielding Review (FR) at the end of the sprint cycle. These reviews throughout the sprint/service pack cycles supplant the traditional PDR/CDR/SVR/PRR reviews and relate directly to the decision points described in the DSB Task Force's (2009) report to Congress, as shown in Figure 5.[2]



[2] Service pack functional backlog, from an Agile development perspective, is a prioritized listing of allocated requirements (in Agile terms, stories) determined at the beginning of the sprint to be sufficient tasking to complete within the sprint cycle. The current backlog is the amount of the service pack functional backlog remaining within the sprint and is used to determine the progress against the planned effort.

Figure 6. Linkage Between DoD Acquisition Mangaement System Reviews and Agile Development Reviews

Given the potential differences in the wide variety of program development efforts, tailoring of the reviews to best support the specific aspects of a program is necessary. This customization can, as indicated previously, be structured such that the sum of the review content is equal to the sum of the replaced reviews.

Just as the reviews themselves are being streamlined, the supporting documentation should be streamlined to eliminate unnecessary effort.

Documentation Analysis

The documentation review resulted in a comprehensive analysis that provides a high-level overview of acquisition documentation. Although it was expected, the review verified that because a program is required to increase reporting responsibilities to address statutory and regulatory requirements, opportunities for significant streamlining are greatly reduced. This is particularly true for Major Defense Acquisition Programs (MDAPs) and Major Automated Information Systems (MAISs). It is the remaining programs that can benefit from a reduction in documentation associated with regulatory requirements; specifically, small software intensive development efforts. This does not preclude the use of Agile development as a component of larger projects (such as for a software development effort ancillary to a major hardware development effort), but it will require a significant amount of negotiation with the MDA.

In analyzing individual document requirements, it was apparent that aggregate generalizations regarding documentation do little to support the tailoring of a program to streamline reporting requirements other than to say that it is possible. As Lapham et al. (2010) reported,

> Those programs that have used Agile in software development have found that the DoD 5000 series has great flexibility and does not in fact preclude the use of Agile. It appears that with careful review and some tailoring an alternate interpretation can be created so that Agile can be used on DoD programs. (p. 13)

This analysis, while correct in identifying the DoD 5000 series as the prime set of regulatory hurdles with which to contend, shows that a program must also deal with additional statutory and other regulatory requirements tied to acquisition development. Even if Service-specific requirements (Secretary of the Navy instructions, Army regulations, etc.) and *Defense Acquisition Guidebook* requirements are removed, several Title 10 requirements and other regulatory requirements remain (such as Chairman of the Joint Chiefs of Staff Instruction [CJCSI] 3010.02B, 3100.01A, 3170.01H, 3312.01A, 6212.01D, and 8501.01A; DoDD 7045.20; DoDI 4650.01, 6055.1, and 7041.3; and Statement of Federal Financial Accounting Standards [SFFAS] No. 23).

The statutory/regulatory documentation breakout resulted in further decomposition to identify value-added versus negligible-value or no-value-added documentation (this was a qualitative evaluation associated nominally with a generic Agile software development effort). Many documentation requirements have little or no value in supporting a software development effort or the eventual fielding of software (such as Programmatic Environmental, Safety, and Occupational Health Evaluation, Non-Destructive Test Plan, and Unique Identification Implementation Plan, Failure Modes Effects Criticality Analysis, Performance Based Logistics Business Case Analysis, and Diminishing Manufacturing Sources and Material Shortages); in these cases, the PM should negotiate with the MDA to

remove or reduce the documentation requirement, as appropriate. There are many cases in which the value of the document to the development effort is obvious, and program management offices should identify those documents early in the program initiation phase to ensure proper planning to accommodate the necessary documentation effort.

A program's milestone reviews and documentation streamlining effort can support a project's Agile development; however, gaining MDA approval for those efforts can be problematic without some assurance that programs are still producing a quality product. RITE provides many of the necessary assurances that programs need to gain MDA approval.

RITE Analysis

As described in the background section, the RITE initiative was created out of a need to improve the ability of programs to meet cost, schedule, and performance targets of their sponsors. In adapting to the needs of Sec. 804, 2010 NDAA, RITE answers many of the concerns of PMs and MDAs regarding the rigor necessary to successfully implement an Agile development methodology.

In following the RITE process, programs use the RITE Pillars (see Figure 7) to guide their efforts in supporting an Agile development effort. RITE focuses a program's efforts on critical areas proven to be essential in successfully developing and fielding software products within cost, schedule, and performance constraints.

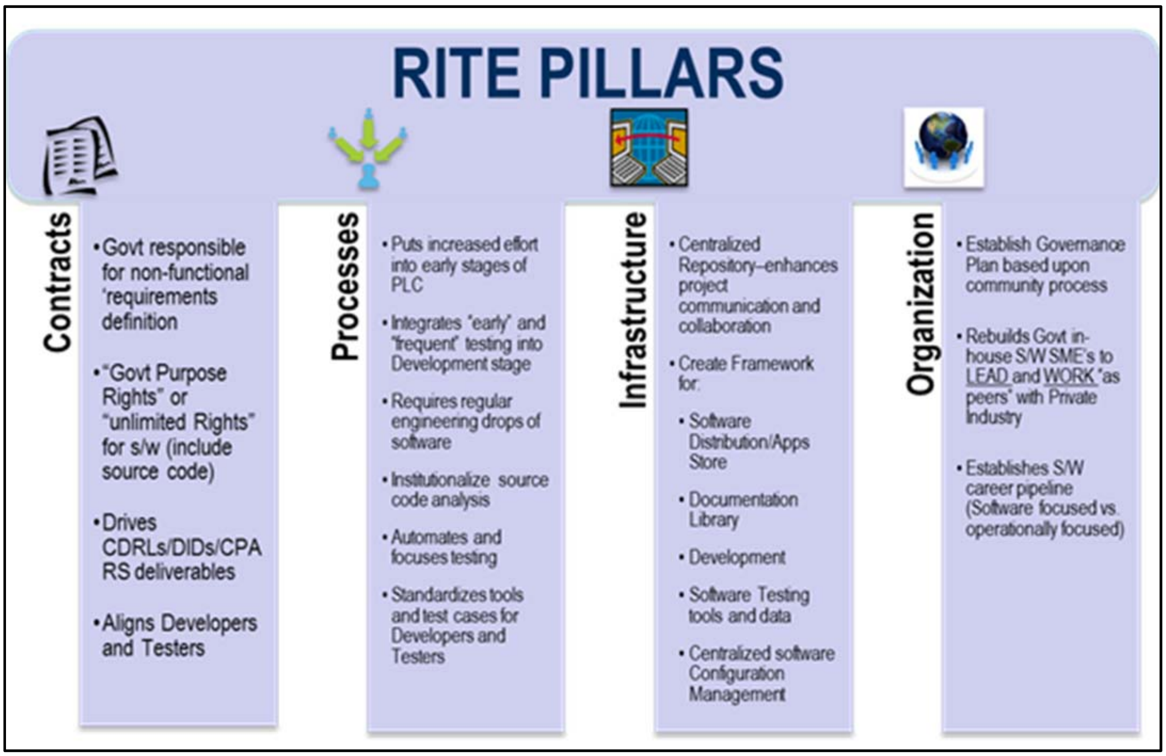


Figure 7. RITE Pillars

The RITE process is not, nor is it intended to be, a panacea for a program struggling with Agile development. It is intended to support Agile development and other simplified, rapid development techniques that focus on product quality and efficient development. Combining Agile development with RITE provides a program with the structured engineering practices necessary for defense acquisitions. The RITE focus on contracts is supported by

Lapham et al. (2011) in analyzing contracting issues associated with Agile development: "Due to the iterative nature of Agile and its propensity to accept (even welcome) change, many contracting vehicles present unique challenges for employing Agile methods. A particular issue is the reporting and milestone requirements often levied against DoD contracts" (p. 33).

RITE also includes focus areas for processes, infrastructure, and organization, which provide necessary supporting elements that give Agile development structure without becoming cumbersome to the development effort. The Process component of RITE puts a greater level of rigor in the development effort and provides the structure necessary to keep Agile development methods on track. The Infrastructure component of RITE provides the tools necessary to support Agile development without hindering flexibility; automating as much of the mundane record-keeping, configuration management, and test tools and data ensures that the development team stays focused on development and not on writing reports and tracking software baselines. The Organization component of RITE focuses on the teaming nature required in an Agile development environment. While it is common to have a software effort completely developed by a contractor, the RITE process has identified key areas in which government personnel support development by integrating users, developers, and the integration/test team throughout the development cycle.

Recommendations

Although the DoD response to the congressional requirement to reform the IT acquisition system referenced all the key components necessary to compel program management offices to consider Agile development methods, little is actionable from the response. The DoD must focus efforts on adapting the DoD 5000 series to address streamlined development methods and provide the regulatory authority to reduce documentation complexity while maintaining appropriate oversight. Pending a significant change to the DoD 5000 series, PMOs can still execute Agile development—but not without addressing milestone reviews, contracting, and documentation.

The milestone review process must transition from monolithic, all-encompassing reviews to smaller, frequent decision reviews focused on meeting development targets. Ensuring flexibility in the process, the reviews must accommodate changing requirements and quality development. The Office of the Deputy Secretary of Defense (2010) report to Congress provides the basic authority to execute IT programs based on this approach (pp. 9–14). The transition to frequent decision reviews must also be accompanied by a streamlined documentation effort.

Maintaining the comprehensive documentation requirements of a standard acquisition program would severely reduce the value of an Agile development. Documentation should be focused primarily on meeting the requirements of the development and sustainment effort. Secondary requirements should include statutory documentation and regulatory documentation that cannot be negotiated away. This negotiation with the MDA must be executed as early as possible in the program initiation phase as soon as documentation requirements are locked down.

Where statutory and regulatory compliance drives requirements outside the Agile development structure, PMOs should ensure that contracts address those elements while maximizing the flexibility necessary to keep Agile development as the primary criteria upon which the contract is evaluated. As Lapham et al. (2011) noted in their assessment of the value of implementing an Agile development methodology to a PMO, engagement above the PMO level is necessary (including the need for waivers, mainly from the MDA) to address the departure from DoDI 5000.02 requirements:

> For example, a PMO that embraces the Agile principle that values operating code over extensive documentation may require a different set of CDRLs when formulating a contract. This not only requires a change in perspective, but also the creation of appropriate governance models, via tailoring DoD 5000.02 and CDRLs from such events as SRR, PDR, CDR, etc. The PMO involved may have to seek waivers from higher up the acquisition chain, and these higher-ups must also understand Agile methods if they are to understand what they are waiving. One of our reviewers cited a recent contract using Agile methods, in which they were bounded by an SDR milestone, but obtained approval to have IDRs (Incremental Design Reviews) beyond that time instead of the traditional PDR and CDR cycle. (p. 24)

PMOs supporting an Agile development effort must work closely with their respective TA to identify and plan a successful acquisition strategy that leverages the best of Agile methods while maintaining the oversight necessary to ensure that a quality product is delivered within cost, schedule, and performance parameters. The PM and TA must present a unified front in gaining approval from the MDA. The TA, providing the institutional backing for Agile development, should champion the effort, while the PM provides program specific details that support the program's streamlining requests.

This interaction between the PM and MDA is essential to the success of any Agile development effort absent significant changes to current acquisition regulations to address the Sec. 804, 2010 NDAA requirements. Implementation of RITE, within the context of an acquisition program's Agile development effort, will assist PMOs in validating and ensuring compliance with critical acquisition elements, which is essential to garner the support of the MDA. RITE is an Agile enabler for the government.

Conclusion

The analysis regarding the effort necessary to streamline a program's milestone reviews and documentation requirements confirm previous research regarding the applicability of Agile development within a DoD acquisition environment. These results require an up-front investment in time and effort to produce a meaningful reduction in the milestone review and documentation effort. PM engagement with the MDA, in concert with the TA, is essential in gaining the approvals necessary to support Agile development. The use of the RITE process supports the PM's objective of creating a structured environment that remains conducive to Agile development and provides the MDA with the comfort level needed for approval of a streamlined milestone review and documentation effort.

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Challenge-Based Acquisition: Stimulating Innovative Solutions Faster and Cheaper by Asking the Right Questions[1]

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Abstract

Budget reductions will require the Department of Defense (DoD) to make difficult decisions on how to invest limited resources and make current programs more affordable. Traditional acquisition methods are lengthy, serial, gate-like processes, built around stringent specifications and arms-length relationships. By contrast, Challenge-Based Acquisition (ChBA) utilizes transparent, accessible, concrete challenges to satisfy warfighter needs and stimulate industry innovation. Challenges enable DoD programs to assess actual performance against clearly defined mission objectives and create incentives for industry to innovate. ChBA thus offers a more transparent approach to fielding new capabilities, upgrades, and enhancements to existing systems.

Mandate for Change

It's time to fundamentally change the way that we do business in Washington. To help build a new foundation for the 21st century, we need to reform our government so that it is more efficient, more transparent, and more creative. That will demand new thinking and a new sense of responsibility for every dollar that is spent.

– President Barack Obama (2009)

Fewer than half of the programs in the Department of Defense (DoD) Major Defense Acquisition portfolio have met established metrics for cost or performance (GAO, 2011a). Even worse, the DoD has canceled entire programs for cost overruns under the Nunn-McCurdy Amendment after investing billions of dollars that could have been used elsewhere across the department (GAO, 2011b). According to the Government Accountability Office (GAO), 50 of 74 breaches involved engineering design issues discovered after production had begun.

Traditional DoD acquisition follows a lengthy, serial process based upon a plethora of documentation as required by the DoD 5000 Series of Instructions and Directives (DoD, 2003b) as well as numerous Service-specific acquisition guidelines. In these documents, mission needs become program requirements, which are then quantified as performance parameters, defined as system attributes, tracked through derived technical performance measures, and included in a government/industry exchange of system specifications. Along this serial path, the linkage of program requirements to mission performance typically becomes unclear and often inaccurate. Alternatively, in some cases, system specifications become far too rigid and detailed, thus stifling opportunities for innovation. Despite best efforts by programs to mitigate risk through verification and validation using the systems engineering process, even a perfectly executed program can still produce a quality product that is often "late to the fight," operationally ineffective, or unsuitable even if it addresses the original mission need.

Furthermore, most contracts are awarded using government source selection evaluations based on industry paper proposals rather than "actual" product performance. This creates an incentive for industry to produce flawless documents with highly optimistic cost, schedule, and performance projections that meet or exceed every requirement in the government's request. As a result, performance during program execution often falls short of the government's expectations and cost and schedule overruns become nearly inevitable. These unrealistic proposals become particularly problematic when there is little prospect for additional competition throughout the acquisition life cycle, which may lock the program into a single solution and provider.

The resulting disappointment creates an arms-length relationship between the contractor and the government, limiting trust, communication, and transparency. This can be particularly problematic given the long life cycle of many defense acquisition programs. The

impact of this tense relationship can raise costs related to bidding and negotiating contracts and slow the process of coming to acceptable terms and conditions (Crook, Ketchen, Combs, & Patterson, 2012). For example, a recent study concluded that the DoD currently spends roughly $400 billion each year acquiring products and services from its contractors, with about $100 billion of that amount spent on administrative costs alone. By cutting unneeded bureaucracy, defense officials could reduce the department’s costs by 20%—or roughly $20 billion each year (Weigelt, 2012).

The complexity of traditional DoD acquisition makes the process difficult for programs with tight budgets or timelines to execute predictably, and virtually impossible to execute when trying to meet an urgent operational need. Given this situation, how can the DoD acquire capabilities both faster and better? The answer includes expressing requirements in terms of general capabilities rather than firm specifications and encouraging industry to respond with applicable product development and innovation that demonstrates best-of-breed solutions.

This paper suggests Challenge-based Acquisition (ChBA) as an approach that could be applied to urgent need situations, could be executed in a more rapid, transparent manner, and would allow program stakeholders to satisfy mission needs. ChBA presents challenges to a set of interested parties, communicates government needs to the private sector, and encourages the creation of innovative products. The challenges are expressed in terms of specific capability criteria that must be satisfied, with the proposed solutions proven by evidence of performance. The ChBA approach leverages practices designed for a rapidly evolving technology environment and meets the real demands of users in the field. It applies acquisition practices and techniques necessary to achieve better outcomes in DoD programs and projects. ChBA is founded on the codification of government needs expressed as concrete performance outcomes. These outcomes are challenges that are issued to a marketplace of competing vendors, rather than needs expressed in paper specification documents that are addressed with unproven paper proposals.

Background

End users have difficulty imagining transformational or inventive solutions when they have a working solution at hand. Soldiers, for example, are good at improvising solutions to address shortcomings of equipment, and using whatever they can find on the battlefield. Similarly, they are experts at assessing the likely success of incremental improvements to devices and techniques. It is hard, however, to extend this innovation beyond the readily conceivable.

Henry Ford supposedly said, “If I had asked people what they wanted, they would have said ‘faster horses’” (Ford, 2006). More recently, Steve Jobs said, “You can’t just ask customers what they want and then try to give that to them. By the time you get it built, they’ll want something new” (Burlingham & Gendron, 1989). Even the brightest equestrians would have had trouble picturing the utility of the Model T. While soldiers, sailors, and airmen are indeed the right individuals to define mission requirements, involving them in the specification process can limit the inventiveness of potential solutions.

But suppose that Henry Ford had heard, “I want to get to my destination faster and with comfort and affordability.” In this case, the users would have issued a concrete mission challenge—get there faster with comfort—rather than a specified solution—a faster horse. Unfortunately, government acquisition agents, like Ford’s public, rarely think in terms of mission challenges and instead think in terms of tighter specifications to define solutions.

As early as the 1980s, the DoD recognized that relying on highly rigid specifications can be burdensome and costly. Even in the unusual cases where specifications and

standards are perfect, premature application, over-application, and inappropriate application of standards could still cause complex problems (Bergman, 1996, p. 32). The DoD enacted acquisition reforms, deleting many military specifications from contracts, and emphasizing outcome and performance-based acquisitions (Bergman, 1996).

Challenges present an option for achieving these goals. Governments and industry have long used challenges to spur technology advances in areas that include agriculture, aviation, energy, medicine, and navigation. For example, in 1714, an Act of Parliament established the British Longitude Prize (Princeton University, n.d.). The Longitude Board, which administered the prize, did not fund technical research but simply promised monetary awards based on the accuracy of proven results: £10,000 for 60 nautical miles of accuracy, £15,000 for 40 nautical miles, and £20,000 for 30 nautical miles. The prize prompted development of the maritime chronometer, which revolutionized global navigation and solved a problem that had bedeviled seafaring nations for over 150 years.

The Wright Brothers' contract with the U. S. Army (Smithsonian, National Air and Space Museum, n.d.) serves as a 20th century example of ChBA. As a result of their airplane's performance in the 1909 U.S. Army flight trials, they received a contract that strongly incentivized speed, with a 10% bonus for every full mile per hour above 40. The average speed of the Wrights' aircraft was 42.5 miles per hour, earning the inventors a $5,000 bonus and bringing the final purchase price of the airplane to $30,000.

For decades, the aviation industry continued to create ChBA-like opportunities. When aircraft operators abstracted away the details of engine design and simply challenged power plant makers to deliver performance in terms of thrust, weight, and efficiency, General Electric's Jack Welch conceived the idea of performance-based logistics. He sold "power by the hour" (Knowledge@Wharton, 2007), which relieved aircraft owners of the need to inventory, maintain, and repair engines. As a result, the costs of engine inventories, maintenance, and repair declined dramatically.

More recently, the defense and aerospace industries have used challenges to support innovative technology development in areas of information technology (IT), space transportation, and military combat systems, as illustrated by the following examples.

Space Transportation. In 2004 Space Ship One, a suborbital air-launched space plane, won the U.S. $10 million Ansari X Prize by completing the first manned private space flight. Space Exploration Technologies Corporation, also known as SpaceX, made history on May 25, 2012, as the world's first privately held company to send a cargo payload, carried on the Dragon spacecraft, to the International Space Station (SpaceX Corporation, n.d.).

Military Combat Systems. Mine Resistant Ambush Protected (MRAP) vehicles are a family of armored fighting vehicles originally designed under the guidance of the U.S. Marine Corps to survive attacks and ambushes involving improvised explosive devices (IEDs). On July 31, 2007, the Marine Corps Systems Command launched MRAP II pre-solicitation, challenging bidders to develop a new vehicle that offered a higher level of protection than the current MRAP vehicles. The U.S. Army Research Laboratory ensured the technologies used in the Frag Kit 6 (Fullerlove, 2009) armor upgrade project would be available to MRAP II designers. Initial testing at the Aberdeen Proving Grounds disqualified vehicles that did not meet requirements; the design run-off identified two vendors whose vehicles could pass the demonstration test.

Information Technology. The federal and commercial markets have taken advantage of the highly competitive, fast-paced environment of IT. Most software manufacturers must prove that their software works within an environment and that it can

integrate into a larger system. Commercial manufacturers often provide free demonstrations at trade shows and tabletop exercises. To incorporate vendor solutions into its Network Integration Evaluation (NIE) program, the Army conducts semiannual events that bring together three Army communities to evaluate militarily useful technologies in both laboratory and field environments. The Army applies the Agile Process to accelerate the identification, testing, and fielding of relevant networked and non-networked capabilities to the soldier, in concert with capability set fielding and the Army Force Generation (ARFORGEN) cycle.

The government has also set up programs specifically designed to make use of challenges. In addition to the Defense Advanced Research Projects Agency's well-known Grand (DARPA, 2004) and Urban (DARPA, 2008) Challenges, they include the efforts summarized in the following section.

Defense Acquisition Challenge (DAC) Program. The DAC program (Defense Acquisition Challenge [DAC] Program, 2012, § 2359b) annually solicits technology proposals from small- and medium-sized enterprises. The proposals present technologies that could lead to improvements in performance, affordability, manufacturing, or operational capability if introduced into existing acquisition programs (DAC Program, 2012, § 2359b). The new technologies should replace or augment some aspect of a current procurement and must be ready off the shelf. The DAC offers a promising way to encourage innovation and help new companies break into the defense market. However, it centers only on improvements to existing, conventional acquisition programs. Ironically, the DAC impels these programs to expend significant resources in order to expose opportunities for innovation that, if successful, will render parts of the original acquisition redundant. In a sense, the DAC represents an example of ChBA in which the challenges are not explicitly designed by the government but inferred by industry from existing, specification-based acquisitions. However, ChBA has the advantage of permitting entirely fresh approaches and avoids forcing industry to accept the constraints of an ongoing acquisition.

Defense Innovation Marketplace. The Defense Innovation Marketplace serves as a centralized resource to help both government and industry "reinvigorate innovation" and fosters collaboration and communication between government and industry beyond traditional Requests for Information and Industry Days. The program allows industry to learn about the DoD's investment priorities and capability needs, and to submit summary reports on proprietary Independent Research and Development (IR&D) to potential customers. For the government, the Defense Innovation Marketplace functions as a one-stop shop for DoD science and technology planning, acquisition resources, funding, and financial information by providing agencies with search tools to access and leverage industry technology projects (DoD, 2013).

Challenge.gov. Outside the DoD, the Office of Management and Budget (OMB) has established the www.Challenge.Gov website, which helps individuals and companies to compete for prizes offered by various government agencies for solving some of their toughest problems. The website supports the "OMB Guidance Memo on the Use of Challenges and Prizes to Promote Open Government," dated March 2010. That memorandum responded to the President's Directive on Transparency and Open Government, which tasked the OMB Deputy Director for Management with issuing guidance for the increased use of challenges and prizes to develop new tools and approaches to improve open government. OMB launched the website in 2011 with 17 different agencies posting challenges with prizes, including a recent VA $3 million prize. A progress report published by the White House Office of Science and Technology stated that prizes may be effective in stimulating solutions to government problems (White House Office of Science and Technology Policy, 2012).

ChBA Attributes and Benefits

ChBA creates an efficient division of labor where the government focuses on what it needs (i.e., demand) to achieve its mission and private industry focuses on solutions (i.e., supply). The government could use ChBA to communicate its needs by framing challenges that are analogous or identical to the desired capability. Industry could then respond to the challenges without being confined by extraneous constraints such as highly detailed engineering specifications.

To meet government needs, the challenges must be transparent and understandable. If possible, the government should make the challenge accessible to all parties wishing to address the stated needs. Concrete challenges can permit nuanced levels of control in acquisition not possible with static specifications alone.

As shown in Table 1, the DoD can derive several benefits from applying ChBA in its acquisitions. They include expanding user involvement, leveraging technology, reducing risk through proof of delivery rather than paper-based proposals, accommodating the full life cycle of a fielded system or product, utilizing the most appropriate contracting methods, and engaging industry to obtain competitive advantage.

Table 1. Acquisition Considerations, ChBA Compatibility, and Benefits

Acquisition Priority	ChBA Attribute	ChBA Benefits
Urgent Warfighter Mission Needs / Accelerated Fielding Timeline	ChBA is well suited to meeting urgent and high-priority requirements. These needs are often very specific and amenable to description as acquisition challenges. Additionally, the urgency of the need relaxes most of the DoD Instruction 5000.02 constraints. (FAR 6.302-2 Urgent and Compelling Need).	ChBA allows rapid development of advanced technology, including both military and commercial variants. It can result in fielding the correct solution the first time, and avoiding additional costs of rework and schedule slippage—ideal for meeting urgent warfighter needs.
Technological Maturity	By definition, ChBA requires vendors to offer mature technology in order to participate in a challenge event.	ChBA allows new functionality and interoperability to be tested in a concurrent environment, ensuring a more operationally ready product and thus reducing testing costs and timelines.
System Life-Cycle Support / Upgrade Considerations	ChBA is best suited for technology-intensive acquisitions, which are likely to be short lived given the rapid pace of technology evolution.	ChBA fits well into short-duration programs, where constraints in the Operations and Support phase of the Defense Acquisition Management System process become irrelevant.
Efficient Contracting Processes	ChBA can be executed using Broad Agency Announcements (BAAs), Indefinite Delivery / Indefinite Quantity (ID/IQ) contracts, Single Awards, Blanket Purchase Agreements (BPAs), or Multi-Award Contracts (MACs).	ChBA can employ a flexible, streamlined contracting process suited to a variety of contracting vehicle types. This enables the program manager to leverage the contracting type that best suits the program's needs and individual tolerance for risk.
Enhanced Industry Competition	ChBA is structured to encourage a diverse range of industry members (including nontraditional defense suppliers), to participate, thus making for a highly competitive environment.	Because ChBA lowers market entry barriers to nontraditional DoD suppliers, it provides enhanced opportunities for competition that may not normally arise within the traditional defense marketplace.

Law, Regulations, Policy, and Guidance

Recent acquisition laws, regulations, and policies emphasize the need to invest in design development and prototyping to mitigate performance risk and cost growth in DoD acquisitions. In the Weapon Systems Acquisition Reform Act (WSARA) of 2009 (Office of the Secretary of Defense, 2009), Congress directed the Secretary of Defense to ensure that the acquisition strategy for each major defense acquisition program includes requirements to demonstrate capabilities using competitive prototypes, and that programs consider appropriate trade-offs among cost, schedule, and performance objectives before development begins.

Likewise, the Federal Acquisition System fully supports acquisition challenges, as indicated by the guiding principles in the Federal Acquisition Regulations (FAR 1.102). Specifically, federal acquisitions must satisfy customer needs in terms of cost, quality, and timeliness of the delivered product or service by

- maximizing the use of commercial products and services;
- using contractors who have a track record of successful past performance or who demonstrate a current superior ability to perform;
- promoting competition;
- minimizing administrative operating costs;
- conducting business with integrity, fairness, and openness; and
- fulfilling public policy objectives.

FAR Part 2.101, Definitions, includes the following provision: “Qualification requirement means a Government requirement for testing or other quality assurance demonstration that must be completed before award of a contract.” The FAR and the Defense Federal Acquisition Regulation Supplement (DFARS) contain regulatory and policy guidance to allow testing of designs before implementation and fielding. FAR 11.801, Pre-award in-use evaluation, states that “supplies may be evaluated under comparable in-use conditions without a further test plan, provided offerors are so advised in the solicitation. The results of such tests or demonstrations may be used to rate the proposal, to determine technical acceptability, or otherwise to evaluate the proposal.”

DoD Directive 5000.01 (DoD, 2003a) requires each military department to establish its own independent Operational Test Agency (OTA) to plan and conduct operational tests, report results, and provide evaluations for effectiveness and suitability. DoDD 5000.01 (DoD, 2003a) further requires the integration of test and evaluation throughout the defense acquisition process. DoD Instruction 5000.02 (DoD, 2008), issued in 2008, requires a Materiel Development Decision prior to a program’s entry into the acquisition process, causing program offices to invest more funds to mitigate technical risk. Such requirements support the use of ChBA as a means to improve testing efficiency and effectiveness across DoD OTAs (DoD, 2003a).

The examples described previously show that acquisition law and regulation already allow demonstration testing to ensure contractor performance. Precedents in which the government has successfully applied ChBA techniques to acquisitions exist in several domains, such as IT and space. Thus, applying ChBA-like methods to satisfy critical needs appears both legal and practical.

An initial review of acquisition regulation and policy reveals when and how ChBA may be best applied.

- Research and development: A Broad Agency Announcement (BAA) procedure provides a competitive acquisition process. If the challenge involves seeking innovative solutions, then it almost certainly falls within the area of early exploration or development.
- Components, sub-systems, or items: The smaller an acquisition, the easier it is to adapt to the acquisition process without the multi-layered FAR (2013) or DoD Instruction 5000.02 (DoD, 2008) provisions or constraints.
- Urgent capability: Field commanders who require rapid action express their urgent wartime needs in Joint Urgent Operational Needs Statements or similar documents. These needs are often very specific and amenable to description as acquisition challenges.

- Short life cycle: Technology-intensive acquisitions are likely to be short lived given the rapid pace of technology evolution. This makes the complex guidance regarding the importance of reducing long life-cycle costs during the Operations and Support phase of the Defense Acquisition Management process essentially irrelevant.

Better Buying Power 2.0

Recent DoD guidance has also emphasized a faster approach to adopting solutions by using rapid acquisition or agile techniques. In his "Better Buying Power" memorandum (USD[AT&L], 2010), the Under Secretary of Defense for Acquisition, Technology, and Logistics recognized the need to make DoD acquisitions more affordable through added investment at the beginning of the acquisition process to ensure a cost-competitive result. The Defense Better Buying Power (BBP) 2.0 initiative (USD[AT&L], 2012) covers several areas in which challenges can be well suited to implement current guidance.

Achieve Affordable Programs

Mandate Affordability. Challenges can be used to mandate affordability by requiring that all solutions meet a specific price target as a condition of participation in the challenge and subsequent procurement. For example, a challenge may specify that the chosen solution shall not cost more than X dollars. Challenge participants may automatically become ineligible for a final contract award unless their solutions meet the unit cost and/or total cost requirements. This approach ensures that all solutions that the government procures using ChBA will meet pre-defined program affordability targets.

Reduce Program Cost and Risk. The government can use challenges to reduce risk through "actual" demonstrated performance before the government commits itself to a long-term contract. Furthermore, the DoD can build testing and certification criteria into the challenge event, thereby ensuring that accepted solutions will meet testing requirements and required performance objectives before they are purchased by the government, thus reducing risk, delivery timelines, and cost.

Incentivize Productivity and Innovation in Industry

Incorporate Innovation Into Production at a More Rapid Rate. Challenges can spur industry productivity by guiding efficient application of research and development resources to meet specific requirements for a concrete capability. Furthermore, because the technology purchased must be nearly production ready at the time the challenge takes place, this mechanism provides an additional incentive for industry to establish an efficient production process that drives down costs and promotes efficiency.

Promote Effective Competition

Emphasize Competition Strategies and Create/Maintain Competitive Environments. ChBA directly supports creation of a competitive acquisition environment because it encourages a wide range of solution providers to participate. Challenges must be open to the greatest possible number of potential participants, since traditional requirements for entering the defense market do not apply in the ChBA environment. For example, in a challenge focused on current performance requirements, previous experience may be irrelevant when it comes time to make a contract award. This key difference enables organizations and even individuals who have little/no defense experience to participate, thus enlarging the competitive landscape.

Enforce Open Systems Architectures and Manage Technical Data Rights. The DoD can also use challenges effectively to support the introduction of open system architectures (OSAs) across the DoD. OSAs require a predefined architecture with open

interfaces for easy integration of components (DoD, 2011). Challenges can be used to develop adaptable technology for key components of open systems. ChBA also permits flexible intellectual property arrangements and opportunities for licensing negotiations that support effective management of technical data rights over the program life cycle.

Roles and Responsibilities

Government Role

The government takes on a new role in ChBA. In traditional acquisition, the government communicates its needs in a specification and must assume that fulfillment of the specification equates to meeting mission needs. However, the specification could be appropriately constrained, under constrained, over constrained, or simply wrong. If the specification is under constrained or wrong, the result is unlikely to meet mission requirements. If the specification is over constrained, the solution will likely not be optimal and might be impossible to implement.

Current incentives encourage contractors to propose solutions to meet over-constrained specifications, even if the constraints create a high risk of failure and, in the process, spend large amounts of money on developing solutions that may never be fully realized. The fundamental flaw in this process is the failure to recognize when over-specifying drives design. To avoid these problems and implement ChBA successfully, the government should consider the following:

Decompose Complex Requirements Into Challenges. The government will need to interpret warfighter requirements and translate them into meaningful challenge events that will give industry the latitude for innovation and get users what they need. This requires the government to have a broad vision and a commitment to success beyond that typically needed to issue requests for proposals or BAAs. Furthermore, the government should ensure that technical details are not over specified, but rather generalized into technology-agnostic capability requirements that can be demonstrated in a challenge.

Generalize User Experience and Needs and Communicate Them to Industry. After gathering requirements from the warfighter and translating them into executable challenges, the government should communicate the scope of the challenges to industry. In doing so, the government admittedly assumes risk, because formulating the challenges requires the ability to interpret and translate warfighter experience and needs in a clear and concise manner, thus enabling industry to execute the challenge.

Find Unclassified Analogues to Classified Situations. The government should employ ChBA to identify possible solutions to classified requirements by utilizing unclassified challenge analogues. In these situations, participants may not know the details of the particular setting in which the government plans to use a solution, and instead would only know the general performance objectives to be met. This approach supports an enhanced competitive environment by enabling those vendors that do not possess the required security clearances and facilities to participate in the challenge.

Design and Execute a Concrete Challenge Apparatus. The government should design challenge-specific execution and evaluation processes that include a plan for communicating challenges to industry, a plan detailing how the challenge will be executed contractually, specific requirements for challenge participation, and detailed evaluation criteria to ensure the challenge evaluation will be fair to all participants.

Perform Quantitative and Qualitative Analysis of Challenge Results. The government should use quantitative and qualitative measurements to evaluate challenge results. More specifically, the government may evaluate the challenge participants during or

immediately after the challenge, and/or over a longer term, as defined by the initial challenge notice. Upon completion of the challenge, the government may opt to

- Purchase one or more of the competitors' offerings based on confidence in the product's utility, as demonstrated during the challenge.
- Refine and reissue the challenge based on lessons learned during challenge performance. This can become part of an incremental government strategy that includes challenge-based research projects.
- Do nothing. If the challenge results did not inspire confidence that any of the products would meet government needs, the government has no obligation to let a contract. This prevents a potentially unsuccessful acquisition.

Industry Role

Industry also takes on a new role in ChBA: one that more closely mirrors how industry normally develops and brings a product to the commercial market versus the traditional defense acquisition market. In this case, industry would be responsible for independently developing a solution that addresses a given capability need (e.g., "get to my destination faster and with comfort and affordability"). This approach contrasts starkly with the traditional defense acquisition process whereby the government provides detailed specifications and requirements (e.g., faster horses) to industry. In the former case, industry bears most of the risk, while in the latter case the risk is borne by the government. Thus, in support of ChBA, industry should do the following:

Innovate. ChBA will demand that industry propose innovative solutions. ChBA is by definition technology agnostic—it does not presuppose one specific, ideal technological solution. Consequently, government will not prescribe a specific technological path that industry must follow, but rather will present its requirements in the form of general challenge objectives that must be met. Industry must then apply its expertise to determine the best technical approach to address the objectives within the schedule/cost constraints provided by the government.

Cooperate With Traditional/Non-Traditional Entities. No single company has a monopoly on innovative solutions. ChBA acquisition, by its very definition, seeks the best technology to address the military's toughest problems. Therefore, industry must be willing to cooperate with any individual or organization that could contribute to a solution meeting challenge performance criteria.

Dedicate R&D Funding. ChBA will require that industry dedicate IR&D funding to develop a solution that meets challenge performance criteria. While the government may choose to provide nominal funding to enable organizations to attend and participate in challenge events, it may not necessarily fund any of the initial development effort.

Negotiate Intellectual Property Licenses. ChBA will require that industry be prepared to negotiate potential intellectual property licenses with the government. As a result, it is important that industry properly identify which of its solutions it derived through exclusive use of IR&D funding versus those that may have been developed at partial or full government expense. Such a distinction is important, because the source of funding dictates the type of licensing rights available to the government.

ChBA Within Defense Acquisition

ChBA is well suited to smaller acquisitions, which are usually not controlled by the full DoD Instruction 5000.02 (DoD, 2008) guidance. In large acquisitions, ChBA can

enhance the standard process by efficiently providing many of the 5000.02-specified components, if not necessarily the entire solution.

Since ChBA is grounded in requirements development and the acquisition process, it does not represent a radical or disruptive break with accepted practice. Instead, it generalizes and builds on existing concepts such as the Defense Acquisition Management System (DAMS), which guides the procurement of major military systems. Figure 1 provides a graphical view of the DAMS phases.

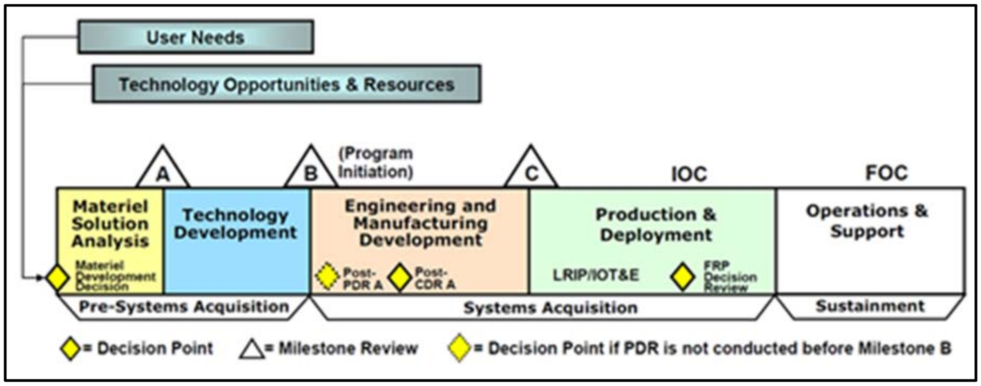

Figure 1. DAMS Phases

The DAMS recognizes the need for an evolutionary approach to acquisition, stating that "an evolutionary approach delivers capability in increments, recognizing, up front, the need for future capability improvements" (DAU, 2011). Increments are managed through repeated application of the Technology Development and Engineering and Manufacturing Development phases. ChBA applies in these early phases of the DAMS and in the general evolutionary approach. Specific opportunities for ChBA application within the DAMS are further described in Table 2.

Table 2. DAMS and ChBA

DAMS Phase	Applicability of ChBA
Materiel Solution Analysis—Assess potential materiel solutions and perform an Analysis of Alternatives. This phase begins when an Initial Capabilities Document is approved that contains an analysis of current mission performance and potential concepts from across the DoD. It ends when the Analysis of Alternatives is complete and materiel solution options, identified in the Initial Capabilities Document, are recommended.	The Analysis of Alternatives enumerates the critical elements needed by each proposed materiel solution. ChBA supplements this step because industry provides the technology needed to create a capability prior to participation in the challenge. If the government does become involved in selecting and maturing technologies, a challenge, based on the needed capability, could be used to explore the range of candidate technologies and assess their maturity.
Technology Development—Determine and mature the appropriate technologies needed for the full system. Critical technology elements, identified in the previous phase, must be demonstrated using prototypes. The Technology Development phase requires the creation of a Technology Development Strategy. For an evolutionary acquisition, the Technology Development Strategy is to include a preliminary description of how the materiel solution will be divided into acquisition increments based on mature technology and an appropriate limitation on the number of prototype units.	A ChBA approach to the Technology Development Strategy is to design a challenge that proves the maturity of each needed technology. The challenge may or may not require a prototype, but will place emphasis on attainment of the technological capability rather than the delivery of a prototype. The acquisition increment requirement of the Technology Development Strategy can be served by a standing challenge that persists through time as multiple challengers demonstrate a range of solutions. A standing challenge gives industry a chance to improve on existing solutions. It also encourages the discovery of game-changing solutions to challenges that have already been solved with more pedestrian technologies.
Engineering and Manufacturing Development—Develop the full system or some increment of the full system capability. This includes full system integration and creation of an affordable and executable manufacturing process.	ChBA potentially eliminates the need for this phase because the technology needed to create a capability is already at or near full capability as a prerequisite for challenge participation. Further, the challenge may specifically require that participants (or their partners) produce fully operational versions of the submissions by a certain point in time following the challenge event.
Production and Deployment—Achieve an operational capability that satisfies mission needs. This includes low rate production for evaluation of major systems and full production or procurement of smaller systems.	Technology acquired using ChBA is by definition nearly production ready; therefore, ChBA can be used to accelerate the LRIP portion of the acquisition process. Furthermore, if operational testing and evaluation criteria are already built into the challenge construct, technology will have met T&E requirements before the government makes a buy decision—again accelerating the IOT&E part of the acquisition process.
Operations and Support—Execute a support program that meets readiness and operational requirements and sustains the system, in a cost-effective manner, over its total life cycle. This phase also includes disposal of the system at the end of its life.	Challenges can be designed to ensure that operations and support requirements are built in from the beginning. As such, a challenge-based demonstration can reenact operational requirements for readiness and sustainment to demonstrate capability before the government makes a commitment to purchase.

The ChBA Process

Figure 2 shows the flow of a hypothetical challenge-based acquisition. The process begins when the government becomes aware of a user's need. The acquiring agency, or its

technical support organization, postulates a capability that can satisfy the user's need. This is a creative process and requires more technical insight than simply recording what the user has requested.

With a desired capability in mind, the government agency creates a set of concrete performance challenges that would demonstrate the ability of the envisioned capability to solve the user's problem. For example, the user problem could be that soldiers need better situational awareness when fighting in urban areas. The envisioned capability could be an information sharing mechanism. A supporting challenge might be to show that solders who use the candidate challenge solution earn better scores in urban combat training than those who do not use the solution.

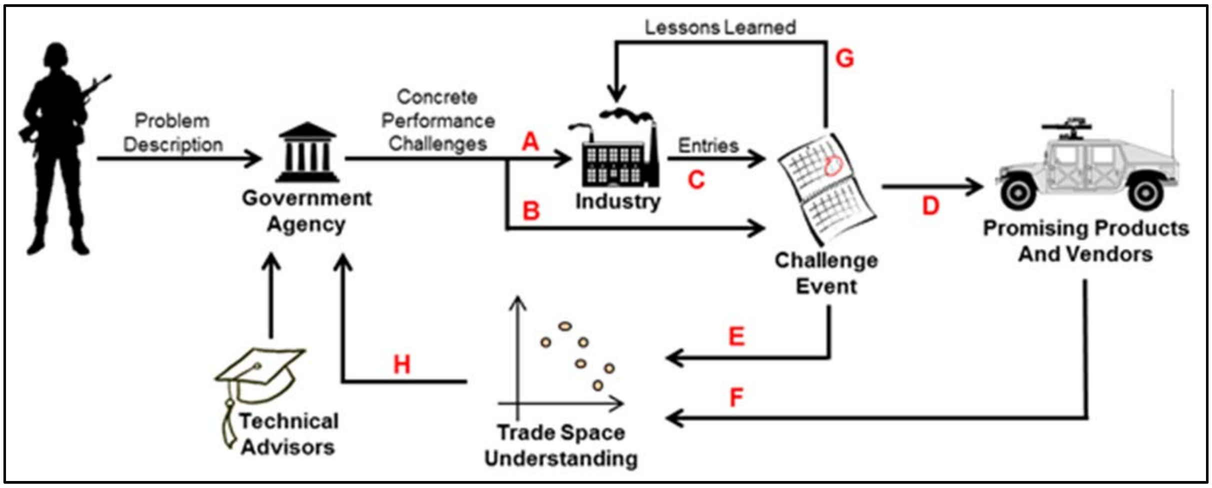

Figure 2. ChBA Process

The challenge event can range from large, periodic, public occasions to private, one-time visits to a testing laboratory.

At Arrow C in Figure 2, industry decides to attempt the challenge. This may produce two results:

- Increased government knowledge of potential solutions and their vendors, depicted by Arrow D.
- Greater understanding of the trade space in which a solution might be found. Arrows E and F show that this understanding comes from both observed performance in the challenge event and information available about promising vendors and their products.

Arrows G and H show that ChBA can be a cyclic process.

- Competitors whose product failed in one challenge may make another attempt after modifying their products. The government may also take this opportunity to fund promising vendors directly. Direct funding rewards vendors for their initiative and incentivizes them to attempt the challenge again, as depicted by Arrow G.
- Based on improved knowledge of the needed capability and the technical trade space, the government can revise the challenge and begin the process again, as depicted by Arrow H. This can be important during the acquisition of complex systems, where multiple steps may be needed to state the challenge correctly or arrive at the appropriate technology.

Case Study—Joint IED Defeat Organization

The mission of the Joint IED Defeat Organization (JIEDDO, n.d.-b) is to "reduce the effectiveness and lethality of IEDs, to allow freedom of maneuver for joint forces, federal agencies, and partner nations in current and future operating environments" (JIEDDO, n.d.-a). In its strategic plan, JIEDDO identifies as one of its enduring capabilities the ability to "employ authorities, flexible resources, streamlined processes, and effective oversight to drive the research and development community to rapidly field C-IED solutions" (JIEDDO, n.d.-a). The computer screen saver depicted in Figure 3 carries JIEDDO's fundamental message to the staff every day. This intensity of purpose and need for rapid action make JIEDDO well suited to apply ChBA.

Figure 3. JIEDDO Organization-Wide Computer Screen Saver

In the summer of 2011, JIEDDO faced the sudden need for a particular class of robot in the war in Afghanistan. JIEDDO demonstrated strength and resolve by issuing concrete challenges that communicated the soldiers' needs rather than reading vendor literature and attending presentations. The challenges were drawn from the suite of Response Robot Performance Standards (National Institute of Standards and Technology, 2011) developed by the National Institute of Standards and Technology (NIST; www.nist.gov). The NIST test method suite includes a range of mobility and duration assessment devices that provide excellent models of the challenges robots face in Afghanistan.

Six vendors accepted the challenge and at their own expense brought their robots to NIST for assessment. Some robots met the challenges as their vendors claimed. Other systems displayed large gaps between promised capability and demonstrated performance. JIEDDO then presented the results of the challenges and the concrete characteristics of the robots to field users in Afghanistan.

JIEDDO discovered that the original request from the field had been over constrained. The challenge performance helped the users to understand the performance trade space and to recognize that one class of robot alone would not meet their needs. As a result, JIEDDO identified two classes of robot that addressed the concerns of two distinct user communities—an important distinction nowhere to be found in the original field request.

In addition to clarifying what the users really needed, the challenge process encouraged vendors to improve their products before the government committed itself to a purchase. The challenge brought transparency and mutual vendor visibility, sparking beneficial competition and product improvement. Within months, vendors asked to return to the NIST, again at their own expense, for another opportunity to confront the challenges and improve JIEDDO's perception of their products' quality. In this way, ChBA enabled JIEDDO to go from the initial request for help to fielded systems in less than a year.

Implementation

Barriers

Barriers to implementation are rooted in the possibility that the government will attempt to manage ChBA in the same way it manages a traditional technology acquisition. While ChBA leverages the DAMS and supporting processes, the acquisition pitfalls that plague these traditional systems could equally undermine ChBA.

Table 3. Acquisition Attributes and Implications for ChBA

Typical Acquisition Pitfalls	ChBA Implications
Mission needs are incorrectly translated through the daisy chain of performance-related documentation, resulting in wrongly defined system performance that is over specified, driving non-optimal solutions.	The DoD may not be able to acquire the most innovative solutions from industry using ChBA if the government dictates specific requirements instead of describing generic capabilities to be demonstrated at a challenge event.
The competitive nature of funding motivates the government to make optimistic predictions of system performance in order to obtain program approval. Likewise, industry is incentivized to propose risky solutions, since this can lead to long-term lock-in and opportunities for contract modifications to address product shortcomings.	ChBA fundamentally does not permit either the government or industry to over-promise system performance. Performance must be proven in a transparent manner prior to the buy decision.
The government often approaches acquisition in a risk-averse manner, requiring extended periods of risk reduction accompanied by documentation requiring multiple reviews. Regardless of risk-reduction efforts, real risk to the government buyer exists due to the late conduct of the Operational Evaluation.	ChBA addresses these risks up front and is ideally suited to high-risk technological solutions. However, ChBA will require cooperation from current document owners and the Operational Test community to avoid this pitfall.

Adopting ChBA

In order for the DoD to adopt and universally implement ChBA across the broader defense enterprise, we recommend that the DoD do the following:

- **Educate acquisition professionals about ChBA.** There is a gap between the latitude allowed by current acquisition law and the state of acquisition practice. Briefly stated, the defense acquisition community culture tends to be highly risk averse even when there are logical arguments to take on additional risk. This cultural dynamic is reinforced as program managers regularly spend money to reduce uncertainty (e.g., risk; Frick, 2010, p. 364). ChBA enables the government to explore potentially high-risk/high-reward solutions in a low-risk environment before vast resources are dedicated to an acquisition effort. This suggests that the acquisition corps needs to be educated on the value of using ChBA in these circumstances.
- **Publicize examples of ChBA success.** The government should publicize working examples of ChBA within the acquisition and supporting professional communities. Acquisition professionals will feel more comfortable embracing ChBA if they can point to other successful programs that use ChBA strategies. Senior leadership must be convinced of ChBA utility so that they will commission a few early adopter programs, and the managers of these early adopter programs must operate under senior leadership imprimatur and

protection. The success of the early adopters will then encourage more cautious program managers to follow suit, provided the results of ChBA are widely publicized across the DoD.

- **Develop a ChBA desk guide as a reference for acquisition professionals.** The DoD should produce a ChBA desk guide to support use of ChBA across the defense enterprise. The guide should be patterned after existing acquisition desk guides to answer day-to-day questions and provide example solutions, practices, and business cases related to ChBA. As ChBA is more widely adopted across the DoD, the desk guide should be updated periodically to document new lessons learned, case studies, and best practices.
- **Consider legislative and regulatory change.** Amend the FAR and revise current acquisition guidance to reflect ChBA as an accepted method to acquire capability for the warfighter. Explicit acceptance of ChBA in published regulatory and policy documents will codify the approach and bring recognition that it represents a sound way of doing business and can achieve high impact in performance improvement.

Conclusion

ChBA can solve a class of acquisition problems defined by industry's tolerance of capital risk and the government's ability to express user needs in terms of concrete challenges. It thus constitutes a logical next step in the current wave of acquisition reforms. ChBA has proven itself in the world of civilian advanced technology acquisition and has been demonstrated successfully in limited areas within the DoD.

Successful application of ChBA demands a renewed government commitment to technical involvement in acquisition, calling upon the acquisition agent to create challenges that, if fulfilled, would also meet the user's requirements. This requires a clear understanding of user need, as well as the creativity, imagination, and technical insight necessary to design the challenge.

ChBA encourages the best performance in industry by freeing companies from constraints unrelated to challenge success. It encourages new players to participate and creates a level playing field for all involved. ChBA adheres to government regulations and is practical to use within the current federal acquisition system. Above all, it offers an efficient means for stimulating industrial innovation and reducing the time and cost of government acquisition programs.

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Defense Acquisition and the Case of the Joint Capabilities Technology Demonstration Office: Ad Hoc Problem Solving as a Mechanism for Adaptive Change

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Abstract

This report describes the preliminary analysis and findings of our study exploring what drives successful organizational adaptation in the context of technology transition and acquisition within the Department of Defense (DoD). It is based on our initial collection and analysis of archival and interview data. We began this study seeking to understand what influences the successful transition of commercial off-the-shelf (COTS) technologies to the warfighter, focusing on the Joint Capabilities Technology Demonstration (JCTD) office as a successful case study. In the course of our investigation, we noted shifts in organization structure, goals, and business processes of the JCTD in response to changing needs of warfighters in Iraq and Afghanistan. Further exploration indicated that these shift were not unique to the JCTD, but were one example of many adaptive solutions to changing needs faced by the DoD acquisition community. This led us to focus our research on better understanding what drives successful organizational adaptation. Our preliminary analysis suggests that ad hoc problem solving may be an undervalued yet broadly practiced skill set within the DoD, which may support adaptive responses to change by the acquisition community. We are currently collecting additional data, which we will use to further explicate our findings.

Introduction

Defense acquisition is a key technical and business function, vital to the success of the U.S. military. However, it is also the focus of seemingly constant critique and reform. Most recently, the rapidly changing global environment and tactics of adversaries have highlighted gaps in the organization's business process capability, intensifying the calls for process reform. It is widely recognized that DoD acquisition must become more nimble and flexible to more rapidly deploy materiel solutions to new and emerging problems and that doing so will require changes in organization structure, culture, and processes. What is less clear is how to gain the most value from investment in change efforts, which can have substantial direct and indirect cost implications. This question is the focus of this report of the preliminary conclusions based on an ongoing qualitative study.

We began this study seeking to understand what influences the successful transition of commercial off-the-shelf (COTS) technologies to the warfighter, focusing on the Joint Capabilities Technology Demonstration (JCTD) office as a successful case study. In the course of our investigation, we noted shifts in organization structure, goals, and business processes of the JCTD office resulting from responses to the wars in Iraq and Afghanistan. Further exploration indicated that these shifts were not unique to the JCTD office but that the shifts we observed were one example of many adaptive solutions to changing needs faced by the DoD acquisition community. In order to better understand technology transition in the current context and in accordance with a grounded research approach, we adapted our analysis plan to focus on what drives successful adaptation (Howard-Grenville, Golden-Biddle, Irwin, & Mao, 2011; Corbin & Strauss, 2008; Lofland, Snow, Anderson & Lofland, 2006). This report is based on our initial collection and analysis of archival and interview data. We are continuing to collect data through interviews and document searches, following a process of theoretical sampling (Locke, 2001; Clarke, 2005) selecting subjects and documents to elaborate on the concepts reported here.

Since 2001 and 2003, respectively, U.S. engagements in Afghanistan and Iraq have highlighted gaps in certain capabilities: U.S. warfighters were not always equipped for the unique challenges they faced under unanticipated scenarios. This was evidenced by casualties incurred and the submission of more than 7,000 urgent need statements (Gansler, 2009). As these conflicts ensued, more than 20 organizations and a variety of business process changes emerged to meet warfighter needs. This situation, and the responses to it, are the focus of the widely cited “Gansler report” (2009), which forms a context for this study. The Gansler report stated, “The essence of the problem is the need to field militarily useful solutions faster,” and “the reality is that the Department is not geared to acquire and field capabilities in a rapidly shifting threat environment” (2009, p. viii). The Gansler report concluded that the ad hoc organizations and effective processes that emerged to meet the unanticipated needs of U.S. forces in Iraq and Afghanistan should be consolidated, codified, and institutionalized. This conclusion is frequently interpreted as criticism of the extant acquisition process and used to justify further expansion of ad hoc solutions (see, for example, *Warfighter Support: DoD’s Urgent Needs Processes Need a More Comprehensive Approach and Evaluation for Potential Consolidation*, GAO, 2011).

In accordance with what is formally termed an “entrepreneurial mindset” (Haynie, Shepherd, Mosakowski, & Earley, 2010), we reframe this interpretation and seek to contribute to positive changes in U.S. defense acquisition through an analysis based on it. Specifically, we explore the implications to DoD acquisition from “standing up more than 20 ad hoc offices, agencies, task forces, funds, and other organizations to respond and fulfill these diverse needs” (Gansler, 2009) and the problem-solving these entities engaged in to emerge as an exemplary case of organizational adaptation to unexpected changes. When conducting qualitative case studies, researchers should “go for extreme situations, critical incidents and social dramas … where the progress is transparently observable” (Pettigrew, 1990, p. 275). Given the tremendous size and bureaucratic nature of the DoD, the vital role of acquisition on the organization’s outcomes, and the sudden and unpredictable external change presented by the September 2001 attacks and subsequent U.S. engagements in Afghanistan and Iraq, we view the acquisition community’s response as an extreme case, justifying focused, qualitative exploration.

Furthermore, we argue that reframing the Gansler report (2009), to view the response as an exemplary, *positive* case, highlights a heretofore under-appreciated skill set, at which the DoD may excel. Based on our reframing and research on organizational routines, dynamic capabilities, learning, and change, we examine the cost and benefits of

investments in this skill set and other business capabilities. Management scholars use the term capability to refer to a high-level, patterned and repetitious routine that confers a set of decision options for producing outputs (Winter, 2003, p. 991). In this report, we will use the term *organizational capability* to distinguish this concept from the concept of a military capability, which is perhaps more familiar to our audience.

This report proceeds as follows. First, we ground the study by describing the organizational context of DoD acquisition and the events that resulted in recognition of the need for rapid fielding. Next, we analyze and reframe the 2009 Gansler report. Then, we describe the case of the JCTD and our methods for analyzing it. We explore the potential costs and benefit implications of different approaches to securing adaptive business responses. We conclude by summarizing our preliminary analysis and describing the next steps in our ongoing study.

Defense Acquisition and the Shock of September 2001

Acquisition is big business. Each year, the DoD spends over $100 billion for research, development, procurement, and support of weapon systems. Acquisition is also a rule-intensive business. In addition to myriad laws governing federal acquisition in the U.S., a plethora of regulations specify how to accomplish the planning, review, execution, and oversight of defense acquisition programs, large and small, sole-source and competitive, military and commercial. Due in some part to the large size and many rules associated with defense acquisition, the organizations responsible for these activities tend to be large and rule-intensive themselves, reflecting the kinds of centralized, formalized, specialized, and oversight-intensive forms corresponding to the classic “machine bureaucracy” from organization theory. The problem is, this classic organizational structure is well known to be exceptionally poor at responding to change. In the context of military transformation, such a problem should be clear and compelling. But which superior organizational approaches are available to acquisition leaders and policymakers? What evidence supports claims of superiority for one organizational approach versus another? Questions such as these are difficult to answer through most research methods employed to study organizations (e.g., case studies, surveys, etc.).

Defense acquisition has been characterized by frequent and extensive critique and reform over the past 50 years leading at least one author to argue that “the only constant in the military’s acquisition system is the continuous reform” (Rasche, 2011). However, driven by the changing demands of warfighters, the commercial rate of technological development, and defense budget constraints, the nature and speed of change in the acquisition system has intensified over the past decade. “Today’s adversaries are changing their tactics, techniques, and procedures at an accelerated pace, heightening the need for U.S. forces to respond rapidly to new threats” (Gansler, 2009). We briefly summarize key reformation events of the past two decades below.

In 1993, then Vice President Al Gore’s *Creating a Government that Works Better and Costs Less: The Gore Report on Reinventing Government* sought to reduce government waste and inefficiency, calling upon the DoD acquisition community to simplify procurement, eliminate regulatory burden, and rely to a greater degree on the commercial marketplace. The Clinton administration was oriented toward “reinventing government” by improving government processes, including procurement. Secretary of Defense Leslie Aspin voiced his concerns that acquisition program costs and schedule problems would threaten the ability of the military Services to continue to acquire the newest technologies that had performed so well during the Persian Gulf War. Aspin proposed a “resource strategy” to allow the DoD to afford the best technology in a times of austerity.

Shortly thereafter, Secretary of Defense William Perry released the memo “A Mandate for Change,” which called for a cultural change within the DoD, shifting the DoD’s focus from the acquisition process to its outcome in the field and asserting that the major obstacles to positive change were internal. Acquisition reform continued under the leadership of Secretary of Defense William Cohen, who, in a 1997, expressed the importance of continuing to reform the way the DoD did business, demanding that the department must be “lean, agile, and focused as our warfighters.” The report’s main assertion was that overhead and support activities be reduced and reallocated to warfighters in light of new threats and constrained budgets. In 2000, “The Road Ahead: Accelerating the Transformation of the Department of Defense Acquisition and Logistics Processes and Practices” detailed the Revolution in Business Affairs (RBA), which called for best practices from the private sector to be implemented in a Revolution in Military Affairs (RMA). The report argued that

> the Department continues to rely on acquisition processes, organizations and infrastructure largely developed in the years following World War II [and] continues to face a limited investment budget, and squeezed by increased operations and support costs from aging weapons systems. (Gansler, 2000)

On September 10, 2001, Secretary of Defense Donald Rumsfeld gave a speech in which he expressed his determination to save the Pentagon from itself. The Secretary claimed that the Pentagon bureaucracy was the “serious threat” to national security, but he clarified, saying, “Not the people, the processes. Not the civilians, but the systems. Not the men and women in uniform, but the uniformity of thought and action that we too often impose on them.” Rumsfeld’s vision for reform included commercial outsourcing of functions not directly related to warfighting to save money, streamlining the system development process to match the private sector’s, and retaining a quality workforce within the military forces and acquisition community. Immediately after Rumsfeld’s call, the events of September 11th occurred, along with the subsequent wars in Iraq and Afghanistan. These soon highlighted gaps in the DoD’s ability to rapidly deploy solutions to its warfighters facing their new scenarios and problems.

In both Afghanistan and Iraq, the rapid adaptation of enemy capabilities highlighted the need for rapid response by the acquisition community. The use of improvised explosive devices (IEDs) in Iraq is a frequently cited example of enemy forces exploiting “capability gaps in the technology, systems, and equipment used by U.S. forces” (GAO, 2011). Combatant commands submitted more than 7,000 statements for urgent solutions, resulting in the eventual creation of “over 20 ad hoc offices, agencies, task forces, funds and other organizations to meet warfighter needs” (Gansler, 2009).

The Gansler Report

In 2009, the Defense Science Board’s Task Force on the Fulfillment of Urgent Operational Needs published a report known widely as the Gansler report, which analyzed the DoD’s rapid acquisition process. The core finding of the report was that major institutional changes needed to be made to the existing DoD acquisition process. The report asserted that “rapid” is counter to the current acquisition workforce culture and that the current ad-hoc system is not sustainable and will not create a permanent solution. Furthermore, the report cited institutional barriers (people, funding, and processes) as powerful inhibitors to successful rapid acquisition within the DoD. Thus, the report argued that not all DoD needs can be met by the same acquisition process and that the DoD must create and codify a separate “rapid” process.

According to the Gansler report (2009), although field commanders were resourceful in acquiring local solutions, the enemy's new tactics exploited the DoD's inability to rapidly field new capabilities. The Gansler report did recognize the efforts of the acquisition community, stating, for example, "It is hard to criticize the industrious nature of those in the Department who have made something happen when urgent needs have been presented" (Gansler, 2009, p. 9). However, its overall perspective and its interpretation in subsequent citations is a largely critical call for reform: "These approaches do not offer a long-term solution" (Gansler, 2009, p. 9). In particular, the report highlighted the ad hoc, work-around nature of the solutions, noting that "numerous rapid reaction programs and organizations have been established in recent years to respond to combatant commander needs—processes that work within and around the traditional system to get solutions into the field" (Gansler, 2009, p. 6), and citing a lack of institutional changes to organize, formalize, and codify the ad hoc approaches as evidence of continued failure.

By and large, the Gansler report (2009) represented the breadth of criticisms of the DoD rapid acquisition process and its ad hoc entities since their emergence shortly after the invasion of Iraq. More recent assessments offer similar criticisms. The GAO's (2011) report to congressional committees in 2011 titled *Warfighter Support: DoD's Urgent Needs Processes Need a More Comprehensive Approach and Evaluation for Potential Consolidation* identified at least 31 separate entities that manage urgent acquisition needs. The report claimed that the numerous points through which a warfighter may submit a request for an urgent need is an example of redundancy and inter-agency overlap. The GAO (2011) asserted that the DoD does not have a comprehensive policy for how urgent needs are to be addressed, lacks visibility over the full range of its urgent needs efforts, has no senior-level focal point to lead the department's efforts to fulfill urgent needs, and has not evaluated opportunities for consolidation, resulting in unnecessary costs. The GAO (2011) ultimately attributed the need for the many ad hoc processes that currently exist to a failure of the DoD to predict change in the external environment, saying, "The department had not anticipated the accelerated pace of change in enemy tactics and techniques that ultimately heightened the need for a rapid response to new threats in Afghanistan and Iraq."

The conclusions and tone of these reports appear critical of the so-called ad hoc solutions. For example, the Gansler report noted, "While these programs have produced significant successes, their ad-hoc, one of a kind nature has created a different set of problems. They rely on learning on the job with little emphasis on support training and sustainment" (Gansler, 2009, p. 6). Perhaps unsurprisingly, given the bureaucratic nature and culture of the DoD, the reports call for centralization, formalization, and codification to correct the problem presented to the DoD organization by the ad hoc organizations and processes. Indeed, we have previously suggested that the DoD has a propensity or preference toward such centralization, to its own detriment (Dillard, 2005). Given the current nature and culture of the DoD, the survival of rapid or urgent fielding capabilities may indeed depend on some form of the solutions recommended in these reports. However, we argue it is important to note that in framing ad hoc responses as a problem and then offering a solution, these reports fail to address the institutional and cultural environment, which they argue cannot sustain innovation. Of perhaps greater concern, it is possible that enacting the recommendations of the reports without full consideration of the value of the ad hoc problem solving that occurred and the costs associated with building a "dynamic capability," the DoD may eventually lose a valuable source of business process and organizational innovation and adaptation and/or may overinvest in a costly organizational solution, when a less costly alternative may suffice.

Research Context: Framing Rapid Fielding

We situate this study in a reframing of the widely cited Gansler report of 2009. Our reframing is conducted in the spirit of the accepted wisdom that creative solutions often require “thinking out of the box” or “lateral thinking” (De Bono, 1967), which we equate more formally with adopting an entrepreneurial mindset—described below—and guided by a research approach based on frame analysis. We undertake this exploration not to argue against specific recommendations of the Gansler report, but rather because we believe that a problem of such persistence and consequence deserves considered reflection from multiple perspectives.

Research Framework

An entrepreneurial mindset is the ability to “think differently,” to sense, act, and mobilize under uncertain conditions (Haynie et al., 2010). Adaptive thinking hinges on “the ability to be dynamic, flexible, and self-regulating in one’s cognitions” (Haynie et al., 2010, p. 218) and is of fundamental importance to entrepreneurs or others facing uncertain task environments. Adaptive thinking is dependent on metacognitive processes—thinking about thinking—which enable individuals to think beyond existing heuristics and knowledge structures in order to be adaptable. A metacognitive strategy refers to the mental framework formulated by an individual, through which to evaluate multiple, alternative responses to processing a task. Researchers have demonstrated that employing a metacognitive strategy can improve the outcome of problem solving by helping individuals avoid using a flawed approach for addressing a problem (Staw & Boettger, 1990; Haynie et al., 2010).

Drawing on these arguments, Haynie et al. (2010) argued that successful entrepreneurs will be those that formulate a metacognitive strategy to generate alternative approaches to thinking about how to accomplish tasks in ambiguous environments. In other words, entrepreneurs who succeed will be those who can develop multiple, alternative ways of thinking about a problem. We approached this research in this spirit, seeking an alternative strategy for thinking about the problem of acquisition reform in order to evaluate possible responses.

A metacognitive strategy requires metacognitive awareness, that is, awareness concerning one’s own thinking. We thus undertook an examination of the logic, assumptions, and links between these and the conclusions presented in the Gansler report. Our examination followed the norms and precepts of frame analysis as developed in organization research (Benford & Snow, 2000; Creed, Langstraat, & Scully, 2002).

Frames are “action-oriented sets of beliefs and meanings that inspire and legitimate that activities and campaigns” created through conversations and written communication that connect events and experiences (Benford & Snow, 2000). Core framing tasks include diagnostic framing, the identification of problems and causes; and prognostic framing, the articulation of a proposed solution. Institutional solutions to problems result when recurring or widespread problems are theorized, or described in general terms, and agreed upon, pointing to a particular solution (Suchman, 1995). Following Creed et al. (2002), we developed a signature matrix to sort the idea elements found in the Gansler report into categories that support the functions of interpretation, argumentation, punctuation, elaboration, and motivation. This allowed us to discern key elements of the frame and consider alternatives.

The Framing of the Gansler Report

The Gansler report (2009) depicted the response to the unanticipated needs of warfighters in Afghanistan and Iraq as evidence that the DoD cannot respond to changing needs. The report framed the emergence of many organizations and the lack systematic,

codified processes as evidence of failure, and problems, which must be corrected. In particular, the report highlighted the lack of sustainable funding for ad hoc processes as a problem for which the solution is codification, centralization, and formalization. Although this is a logical solution to the problem as framed in the report, an alternate frame might suggest other possible solutions.

In the Gansler report, the large number of requests to meet urgent needs, and the highly visible problem of IEDs, are used to support the assertion that the DoD "lacks the ability to rapidly field new capabilities" (2009). The text of the report includes the phrase "in a systematic and effective way," linking the assertion of failure and a lack of systematic processes to ineffectiveness. This depiction is further linked to an overall presentation of the problem or the diagnostic frame; the lack of systematic processes makes the current solution unsustainable, and as the problem is the lack of systematic processes, the solution is therefore the creation of a systematic, codified process in a formal, centralized organization. The latest update of the Joint Capabilities Integration and Development instruction, CJCSI 3170.01H (2012), already reflects some implementation of this recommendation.

Although some successful outcomes result from ad hoc organizations and business processes, recognition of achievements are followed by critiques of the processes that achieved them. Variation is presented as redundant and costly. Ad hoc problem solving is not systematic or codified (and linked to ineffective and unsustainable). Workarounds, although recognized as necessary, are depicted as "disjointed" (linked to unsystematic and ineffective). For example,

> Over the past five years there have been many success stories and lessons Learned. … However, in the larger picture, the DoD has not made major, institutional changes in budgeting and acquisition essential to posture itself for the ongoing hybrid warfare reality. DoD is not systematically prepared to anticipate and respond to urgent and dynamically changing needs that will be a permanent part of 21st century operations.

When progress is noted, it (progress) refers to codification, as in this example:

> The Joint Staff, COCOMs, and the Services have all codified in directives new processes to identify urgent needs and provide rapid responses. Recent progress includes a detailed urgent needs process memorandum circulated by the Secretary of the Navy in March 2009.

The arguments of the report support the recommendation to restructure the organization and to create a codified, systematic process for rapid fielding. This recommendation is consistent with the bureaucratic nature and culture of the DoD and with past routines for codifying, reorganizing, and centralizing. However, a reframing of the problem allows a deeper consideration of factors mentioned but not emphasized in the report and illuminates heretofore underemphasized or overlooked implications of the report's recommendations.

An Alternate Perspective

We explored the question "What is the most cost effective means of achieving the dynamic and adaptive business capabilities DoD seems to require?" We began by reframing the Gansler report. A summary of our analysis and reframing is shown in Table 1. In our reframing, we considered the establishment of 20 (and eventually more than 30) organizational entities over a period of a few years and their development of associated

business models and processes to be *an amazing adaptive response* to an external shock by a bureaucratic organization, which would be expected to be hampered by severe inertia.

Table 1. Framing of the Gansler Report

Focal event	*Warfighters in Afghanistan and Iraq have unanticipated equipment needs*		
	Gansler Frame	**Representative Quote**	**Alternate Frame**
Depiction	DoD has not responded/cannot respond.	DoD lacks the ability to rapidly field new capabilities to the warfighter (*in a systematic and effective way*).	Acquisition community responded.
Punctuation: What is the problem?	Current rapid fielding process is unsustainable.	The essence of the problem is the need to field militarily useful solutions faster. Current approaches to implement rapid responses to urgent needs are not sustainable.	Adapting (business organization) to changing environment. Current process is an example of a valuable, periodically utilized skill-set.
Elaboration: What factors contribute?	Variation is redundant and costly.	The procedures these organizations have developed … vary across the DoD … definitions and regulations that apply to the processes vary [and words] … are sometimes used in conflicting and overlapping ways.	Variation is a necessary component of change.
	Ad hoc problem solving is problematic.	Their ad hoc, one-of-a-kind nature has created a different set of problems. They rely on learning on the job with little emphasis on support, training, and sustainment.	Ad hoc problem solving is a "low cost" skill set.
	Workarounds contradict the institution.	All also utilize workarounds … to sidestep traditional acquisition and fielding process, but these are generally disjointed.	Workarounds allow creativity within a bureaucracy.
	Formalization, codification, and consolidation result in sustainability.	DoD needs to codify and institutionalize "rapid" acquisition processes and practices.	Codification is costly. The full value lies in the knowledge gained through the process, gaining full value requires collaboration.
Motivation: What action should be taken?	Undertake structural reforms to institutionalize a specific solution.	The Secretary of Defense should establish a new agency.	Evaluate costs/benefits of ad hoc solutions and seek solutions that retain diverse skill sets.

Our perspective is not without precedent, even within the DoD. In a 2011 report, *Lessons Learned From Rapid Acquisition: Better, Faster, Cheaper?,* Colonel Robert A. Rasch examined the impacts of wartime acquisition initiatives on the DoD acquisition systems. Rasch framed the continual reform of DoD acquisition as a possible indicator of positive adaptive change. Perhaps best known is the large scale and rapid acquisition of at least 7,000 Mine Resistant Ambush Protected (MRAP) vehicles in just over two years. The need for MRAP vehicles was initially articulated, in February of 2005 by Marines who needed protection from IEDs, RPGs, and small-arms fire. The need was met through a variety of ad hoc solutions involving innovative adaptations to standard processes for

establishing requirements, evaluating progress, and contracting. This instance is cited as an exemplary outcome in GAO reports (GAO, 2009).

Viewing this response above as a successful solution suggests a reconsideration of the definition of the problem. The Gansler report (2009) is clearly focused on the immediate need for rapid fielding, as tasked, and our reframing should not be viewed as a criticism of those efforts. However, when given the luxury of reflective consideration afforded a research project (as opposed to the task specific demands facing a decisively engaged military force), the context of the organization, past attempts at reform and an environment characterized by unpredictable events, suggest a broader and persistent need for business adaptability. We reframe the problem in terms of this broader need: The DoD must adapt its business model and processes to meet unpredictable demands from the external environment. This need is recognized in the Gansler report:

> The global landscape has changed the national security environment, demanding the ability to rapidly access and field capabilities from any source. Agile adversaries are taking advantage of important, globally available technologies by rapidly creating and fielding highly effective weapons. Moreover, the nation faces a vast range of potential contingencies around the world. … This set of circumstances calls for rapid adaptation on the part of the United States as well—*adaptation of tactics, techniques, and procedures* [emphasis added] as well as the ability to field new [warfighting] capabilities on a timeframe unfamiliar to the bureaucratic processes that dominate acquisition in the Department of Defense today. (2009, p. 3)

However, the overriding focal problem highlighted by the framing of the Gansler report is the need for a rapid fielding capability. Reframing the problem as we have done suggests a reconsideration of the role and value of variation, ad hoc problem solving, and codification. The Gansler report frames these factors as contributors to the problem. In our reframing, we considered the role of variation as precursor to change, workarounds as a mechanism for allowing creativity within a bureaucracy, and the benefits of codification as deriving from the process of articulation and clarification as much as (or even more than) from written output. Our reframing suggests a need to evaluate the costs and benefits of ad hoc problem solving versus codified business capabilities and to seek overall solutions that most efficiently support the business adaptability in an unpredictable environment.

Research Approach and Methods

We began our study of the JCTD case with the question of what best influences the successful transition of commercial-off-the-shelf (COTS) technologies to the warfighter. During our initial investigation, we noted shifts in organization structure, goals, and business processes of the JCTD office in response to the wars in Iraq and Afghanistan. In accordance with a grounded research approach (Howard-Grenville et al., 2011; Corbin & Strauss, 2008; Lofland et al., 2006), we adapted our analysis plan to focus on how the organization was adapting to change. This report is based on our initial collection and analysis of archival and interview data. The organization is once again adapting as the need for rapid fielding in Afghanistan and Iraq diminish, and our analysis to this point must thus be considered preliminary. We are continuing to collect data through interviews and document searches, following a process of theoretical sampling (Locke, 2001; Clarke, 2005).

We began this study with a review of literature related to the JCTD office and the evolution of defense acquisition processes. We also conducted a round of exploratory interviews with subject matter experts in the JCTD office. These were informal, unstructured interviews, designed to familiarize us with the history, operations, and evolution of the office.

We encouraged experts to elaborate on these topics and took detailed notes. In the course of the initial data collection, we noted an apparent and deliberate shift had occurred in the mission of the JCTD office in recent years, from demonstrating advanced militarily useful concepts with promising technologies towards rapid fielding of materiel and the importance of ad hoc problem solving.

We collected additional data from two sources: a “snowballing” Google search and the Internet Archive (Nardon & Aten, 2008; Aten, 2010). On Google, we searched for all pages and documents with JCTD or ACTD and the word *technology* in the title from the year 2000 to the present and saved each as a PDF, yielding more than 2,000 pages. We then followed links to identify additional pages and documents, yielding an initial 247 saved PDFs. We scanned all of the documents and excluded documents such as glossary pages, descriptions of acronyms, and descriptions and press releases related to particular JCTDs. This yielded a dataset that included presentation slides, JCTD announcements and policies, and descriptions of the organization.

Next, we collected data from the Internet Archive (2009), “a non-profit organization that was founded to build an Internet library, with the purpose of offering permanent access for researchers, historians, and scholars to historical collections that exist in digital format.” The Internet Archive is searchable by URL with a search resulting in a list of hyperlinks to web pages for the specified URL, by date, that are included in the archive. Thus, one can view web pages of an organization as they existed for a particular year in the past. The archive for the ACTD and JCTD was intact, with multiple instances captured every year from 2001 to the present. We reviewed one web page per year, adding instances as necessary when we noted major changes to ensure that we did not miss relevant documents. On each page, we followed links and printed PDF files of web pages and documents related to the evolution of the JCTD office. We selected pages and documents available from links titled introduction, guidelines, Q&A, links, organization, and what’s new. Our saved documents included conference presentation slides, management briefings, procedures and guidelines, organization charts, and the text of speeches. We did not save specific JCTD project descriptions, glossary pages, or point of contact information pages.

We organized all of the documents by year and imported them into an Nvivo qualitative data analysis software project. We used Nvivo to code the data into broad categories suggested by our previous analysis: organization structure, business model (mission/goals, value proposition, measures), technology characteristics (maturity level, use, customer), and process characteristics (requirements, steps). We then generated reports allowing us to view examples from the broad categories across time.

Research Setting: The Joint Capabilities Technology Demonstration Office

The JCTD program began in 1994 as the Advanced Concepts Technology Demonstration (ACTD), with the aim of more rapid prototyping and fielding of technology for the DoD by demonstrating and assessing the of the military utility of a technology. Over the 18 years since its inception, the overall mission of the program has remained unchanged.

History and Purpose

In the late 1980s, the President’s Blue Ribbon Commission on Defense, also known as the Packard Commission, was charged by Executive Order 12526, in which President Reagan asked the commission to conduct a defense management study focusing on the budget process, the procurement of systems, the legislative oversight, and intra-government organizational arrangements in regard to defense. Among other things, the report indicated a high need for prototyping. The report stated that

> a high priority should be given to building and testing prototype systems and subsystems before proceeding with full-scale development. This early phase of R&D should employ extensive informal competition and use streamlined procurement processes. It should demonstrate that the new technology under test can substantially improve military capability, and should as well provide a basis for making realistic cost estimates prior to a full scale development decision. This increased emphasis on prototyping should allow us to "fly and know how much it will cost before we buy."

The Packard Commission report, as well as several other Defense Science Board reports, led to the establishment of the ACTD. ACTDs are user-oriented and of a large enough scope to establish military utility. During the ACTD, the users (the warfighters) determine whether they will begin acquisition of the new technology. The ACTDs/JCTDs serve the Combatant Commands (COCOM) by fulfilling capability gaps the Services may not view as mission-critical but that the COCOMs are nonetheless requesting.

In 2006, the ACTD became the JCTD. Although the core staff and office remained the same, the name change brought with it a change in focus; there was a shift to emphasizing the fulfillment of capabilities and an added emphasis on transitioning new technologies to the field for sustained use. Despite some changes in management, name, and participation of various agencies, the organizational structure of the ACTD/JCTD has remained fairly constant. An ACTD/JCTD is jointly sponsored and managed by a supporting user (the military) and the technology developer. Approval of ACTD/JCTDs is given by the Deputy Under Secretary for Advanced Systems and Concepts (DUSD [AS&C]). The ACTD/JCTD program maintains a significant cross-service, cross-agency involvement with a heavy focus on joint operations and COCOM participation. In September 2009, the DoD established the Office of the Deputy Assistant Secretary of Defense for Rapid Fielding (ODASD[RF]). Sometime shortly after its establishment, the ODASD(RF) was designated as the overseeing agency of the JCTD program.

Although the personnel and management remained the same, the JCTD program claims to be implementing a new and enhanced business process to better meet the DoD's transformational goal of becoming capabilities based. JCTDs focus directly on the COCOM's most critical warfighter needs and proved a faster, more agile and integrated joint response to emerging asymmetrical threats. JCTDs emphasize increased upfront transition planning, provision for a higher level of OSD funding during the first two years, and bridge funding from Budget Activity Four for those projects that demonstrate compelling joint military utility. In the move from ACTD to JCTD the program eliminated several of the review processes, such as the so-called Breakfast Club, and limited the involvement of the Joint Chiefs. The program was redirected to focus more on capabilities and transitioning the new capabilities but also on rapid fielding; the ACTD program saw a 50–60% transition rate, as the JCTD program is seeing an 80–90% transition rate.

Technology

An important part of considering candidates to become an ACTD/JCTD is the technology readiness level (TRL). "Technology maturity is a measure of the degree to which proposed critical technologies meet program objectives; and, is a principal element of program risk." The DoD Component Science and Technology (S&T) Executive directs the technology readiness levels and determines the level of maturity of a given system.

There are nine TRL levels, each representing a major step forward in the development process of the system. ACTDs/JCTDs are largely previously proven technologies that will, by and large, have a TRL of 7, 8, or 9. A system that is ranked with a

TRL 7 has demonstrated "an actual system prototype in an operational environment." TRL 8 is assigned to technology that "has been proven to work in its final form and under expected conditions." In almost all cases, this TRL represents the end of true system development. TRL 9 is assigned to technology "in its final form" and that has been proven through successful mission operations.

There are several characteristics for which ACTD candidates are chosen: affordability, interoperability, sustainability, and potential for evolution. The affordability of a new capability was viewed from the perspective of the total ownership cost, to see whether the cost of the capability throughout its life cycle would hinder its eventual inclusion into the regular acquisition process. The new technology or capability was required to be interoperable because of the importance of implementing the technology in future operations. The new systems remain in the field, so sustainability was a crucial aspect. Finally, systems and capabilities were evaluated based on their potential to be updated as the situation or threat evolved.

The TRL of ACTDs fluctuated depending on the type of system and the level of risk that managers and oversight organizations were willing to take. In the period before 2003, projects were much larger and assumed more risk in term of the readiness of the technologies (Global Hawk and Predator). The Defense Advanced Research Projects Agency (DARPA) was once one of the largest contributors to the funding of ACTDs; however, eventually DARPA's involvement in the program waned, and so too did the large and risky nature of many ACTDs.

As the ACTD transitioned to the JCTD and as time went on, the program became more focused on picking "the low hanging fruit" in the sense that ACTDs became more focused on smaller projects that assumed less risk. This has also been attributed to the increased focus of rapid fielding that was generated by the wars in Iraq and Afghanistan. Figure 1 shows the relatively steady decline in the average estimated costs of the ACTD/JCTD projects by year for the last 10 years. The decline in costs coupled with the decline in the average length is evidence that lends itself to the notion that the program was, as one official put it, focused on "getting something out the door as quickly as possible."

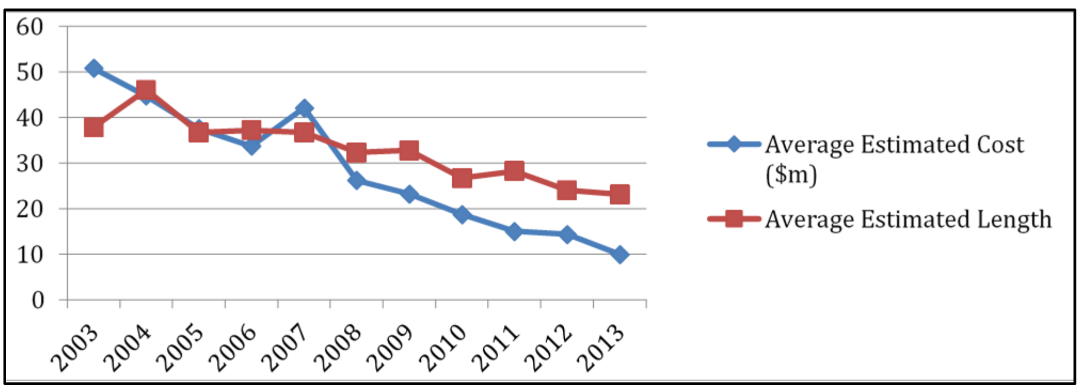

Figure 1. Average Estimated Costs of the ACTD/JCTD Projects by Year for the Last 10 Years

More recently (in last few months) and after a change in management, the JCTD has encountered criticism for its increasing aversion to risk, which was generally coming from senior leadership of the program. Also, the need for rapid fielding has been lessened by the ending of the Iraq War and the winding-down of operations in Afghanistan. Now, there is an emerging desire to shift the JCTD back to its original style of bigger, better and riskier and to adapt once more.

Dynamic Capabilities and Ad Hoc Problem Solving: Pathways to Adaptability

Although the political environment is not perfectly analogous to the business environment, some useful comparisons can be made. The shocks of 9/11 and enemy innovations suggest the acquisition community is facing, and will continue to face, a turbulent environment. Studies of organizations operating in turbulent environments have focused on understanding the role of routines in change and adaptation. Scholars have argued that dynamic capabilities, or the ability to systematically change existing organizational routines are a key to success (Teece, 2007). However, Winter (2003) argued that the costs of creating dynamic capabilities may not be justifiable in turbulent environments. Winter's (2003) argument, along with a recent discussion of anticipated consequences in such environments (Selsky et al., 2007), suggests that ad hoc problem solving may be an effective solution for adapting to change. We discuss these ideas below.

Understanding organizational adaption and change is a key focus of organizations scholars. Organizational routines provide one avenue for exploring how organizations change their capabilities. Organizational routines are the basic components of organizational behavior and are a crucial to understanding how organizational capabilities are accumulated, transferred, and applied (Becker, Lazaric, Nelson, & Winter, 2005). Thus, organizational routines provide a useful starting point for an exploration of the pathways to organizational adaptability. The discussion below draws largely from Winter's (2003) "Understanding Dynamic Capabilities."

An organizational routine is highly patterned, repetitious behavior that is learned, founded at least in part in tacit knowledge and directed toward specific objectives. Thus, behaviors to run a particular production line to produce a particular product constitute a routine. Organizational improvisation is not a routine because it is dynamic, one of kind, and conscious rather than patterned, repetitions, and tacit behavior. An organizational capability is a high-level routine that confers upon an organization's management a set of decision options for producing a particular type of output.

Recent research on strategy in rapidly changing environments has focused on dynamic capabilities (Teece, Pisano, & Shuen, 1997; Eisenhardt & Martin, 2000). Despite the name, dynamic organizational capabilities are based on routines and patterned, repetitious behavior. The dynamic refers to the focus of the routine. Ordinary organizational capabilities are operational capabilities. Those organizational capabilities that provide value exhibit technical and environmental fit, allowing an organization to "make a living" by performing a particular function well and also by allowing an organization to succeed within a particular environment, respectively. Dynamic capabilities are organizational capabilities that extend, modify, or create ordinary capabilities, helping organizations shape and adapt to the environment, achieving evolutionary fitness. Dynamic capabilities involve sensing and shaping opportunities and threats, seizing opportunities, and maintaining competitiveness by combining, enhancing, protecting, and reconfiguring tangible and intangible assets. Zollo and Winter (2002) defined a dynamic capability as "a learned and stable pattern of collective activity through which the organization systematically generates and modifies its operating routines in pursuit of improved effectiveness" (p. 340). Examples of dynamic capabilities include systematic methods for changing operating routines and organizational capabilities for process research development, restructuring and re-engineering, and post-firm acquisition integration.

According to Zollo and Winter (2002), dynamic capabilities are created through three learning mechanisms: experience accumulation, knowledge articulation, and knowledge codification, as shown in Figure 2 Knowledge articulation occurs when individuals express their opinions and beliefs, challenge each other's viewpoints, and engage in constructive

confrontations. Knowledge articulation is a deliberate process through which groups and individuals seek to understand what works and what does not to complete a particular organizational task. Organizational and individual competence is enhanced when implicit knowledge is articulated through discussion, debriefing sessions, and assessments of past performance. These processes serve to improve individuals' understanding of the causal mechanisms that link actions to outcomes. Articulation requires significant effort but can produce improved understanding of changes in links between action and performance. Articulation can thus result in adaption of existing routines.

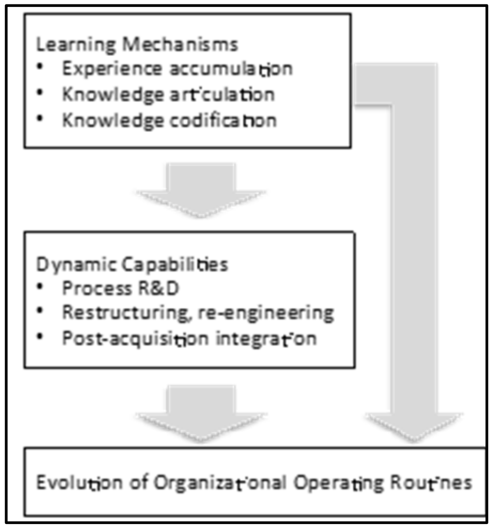

Figure 2. Learning, Dynamic Capabilities, and Operating Routines
(Zollo & Winter, 2002)

Knowledge codification, occurs when articulated understandings are captured in writing, as in, for example, manuals, decision support systems, or project management software. Knowledge codification requires greater effort than articulation. Codification is challenging because it can be difficult to ensure that codified guidance is adequate, and also that such guidance is implemented and followed. The additional effort means that codification may be costly. Costs include the time, resources and attention invested in the development of task-specific tools, as well as the indirect costs of a possible increase in organizational inertia (because the now-codified routine is applied regularly, making change more difficult) or the inappropriate application of a codified routine.

The development of dynamic capabilities is costly. Investments include financial, temporal, and cognitive resources that are directed toward improving understanding of action-performance linkages. The level of investment can be considered along a continuum. It will be lowest when a firm relies on the accumulation of experience in a semiautomatic fashion and more costly when the firm relies on knowledge articulation and even more so for codification. Dynamic capabilities require specialized personnel, committed to change roles, and, to be economically worthwhile, an opportunity to be exercised.

According to some scholars, organizations operating in rapidly changing business environments require dynamic organizational capabilities, which can be "harnessed to continuously create, extend, upgrade, protect and keep relevant the enterprise's unique asset base" (Teece, 2007, p. 1319). However, although dynamic capabilities have attracted attention, they are not the only means of organizational adaptation and change. Firms can also adapt and change through ad hoc or one-time problem solving. Ad hoc problem solving is not repetitious and highly patterned. It typically occurs in response to unpredictable events

in the environment. Whereas the development and maintenance of dynamic capabilities requires ongoing specialized investments in personal and attention, the costs of ad hoc problem solving disappear when there is no problem to solve. The costs of ad hoc problem solving are largely opportunity costs associated with the attention given the problem. If the problem is no longer presented, attention shifts and costs are relieved. Thus, so-called routine capabilities, augmented when needed with ad hoc problem solving, may be the more cost effective response to achieving organization adaptation (Winter, 2003).

The responses of the acquisition community to the change in warfighters' needs, exemplified in this study through the case of the JCTD office, can be considered a successful example of ad hoc problem solving. The reaction of the community; creating organizations and processes to fill a particular need from existing organizations, budgets, and processes; learning on the job; and forging one-time solutions are all examples of ad hoc problem solving, creative innovation to a particular problem.

As discussed previously, such problem solving may be more cost effective than creating a dynamic capability. This is particularly true when an environment is ambiguous and unpredictable or competitors are likely to copy one's success. The long-term response to the need for rapid fielding during the conflicts in Iraq and Afghanistan should take into account the "success" of this problem-solving approach. An evolutionary approach to organizational change would suggest that the variation of organizations and processes be subject to environmental selection, whereby only those exhibiting fit with the environment are likely to survive. Thus, if in fact rapid fielding remains a paramount need, we would expect the creativity that fostered the organizations that met that need to find a way to continue to meet it. History suggests that those within the DoD are adept at doing this. Alternatively, however, if rapid fielding is not required, the costs of developing this "dynamic capability" may be misplaced.

DoD acquisition has exhibited a long history of resistance to change. Given the bureaucratic make-up of the DoD and the size of the organization, this is not surprising. Further, bureaucratic processes are appropriate in some situations (particularly those involving great risk) and may be a necessity for the DoD. However, as many have noted, DoD organization structure and processes were well adapted to the post-WWII–Cold War era, and since 2001 that stable environment no longer exists. Thus, many DoD routine capabilities may have technical fit—they fit well with a particular function, such as the acquisition of large, complicated weapons systems to meet the needs of many players when time and money are abundant—but may not fit with the new environment. The question then becomes, what is the best way to adapt to the new environment.

One must be somewhat cautious in making direct comparisons between the competitive business environment—where success is generally defined as earning greater financial returns than one's rival—and the multifaceted environment facing the DoD acquisition community. The discussion above suggests that ad hoc problem solving should not be discounted out of hand and without consideration. Such solutions allow the DoD to adapt in low cost manner without attempting to change the overall bureaucracy. Although developing dynamic organizational capabilities may be possible, doing so is clearly costly and difficult, as exemplified by the many failed attempts with the DoD and in industry. An alternate perspective on ad hoc problem solving suggests that these solutions should be rewarded, and perhaps structural changes should be designed to allow such solutions to emerge and dissipate as needed, rather than automatically seeking codification, centralization, and formalization. This is particularly salient if one considers that the environment may continue to change. The organizations and processes that have emerged and evolved to exhibit technical and environmental fit for the environment following the

September 2001 attacks may not fit the environment of the future. Ad hoc problem solving is a low-cost alternative for allowing adaptability within the large bureaucracy.

Implementing Change—An Additional Consideration

As noted above, this research suggests that reforms should consider how to take advantage of the ad hoc problem solving skills of the DoD acquisition community. Furthermore, the discussion suggests that, when codification of learning is undertaken, then much of the value of such efforts lies in the process, rather than in the end. Capturing this value requires a collaborative, “safe” environment that facilitates knowledge sharing. The acquisition community can be viewed as a system, composed of many different types of actors and organizations, operating in an uncertain environment subject to shocks and subsequent turbulence. Although, some competition within systems is beneficial, a long history of research documents the deleterious effects of competitive environments on knowledge sharing at the individual level and of prices wars and “hyper-competition” on industry profitability at the systems level. Policymakers should be aware of the potential consequences of such negative competition and structure reforms to minimize its likelihood.

Scholars argue that in business landscapes characterized by great turbulence, traditional competitive actions may not lead to an advantage but may rather result in further turbulence. For example, organizations relying on dynamic capabilities to “turn themselves into moving targets” moving faster, changing more quickly to avoid being “leapfrogged” by competitors, may increase field level turbulence (Delapierre & Mytelka, 1998, p. 78; Selksky et al. 2007, p. 79). Selksy et al. (2007) argued that success in turbulent environments hinges on collaborative endeavors to develop new field level processes, adaptive skills, and capabilities. Selsky et al. (2007) illustrated these dynamics referencing a pair of studies of hospitals in hyper-turbulent environments. In response to changes in federal Medicare reimbursement programs, the states of California and Minnesota each made major reforms to their healthcare systems, resulting in a turbulent business environment. However, the healthcare industries in the two states experienced different outcomes.

In 1982, California adopted a managed competition program in healthcare, creating incentives for providers to compete on price for government care for indigent citizens. At the same time, the federal government changed Medicare reimbursement procedures. Together, these events resulted in unanticipated turbulence in the business landscape of the state’s hospitals.

California’s hospitals reacted immediately, over one six-week period during the study, two hospitals merged, one was acquired, and seven out of 30 hospitals experienced CEO succession. The hospitals entered mergers, alliances, and partnerships between hospitals, physicians, and insurance plans. These actions challenged traditional rules of competition within the industry, understandings about the domain and identity of hospitals, and the traditional boundaries between players in the healthcare field. For example, insurers became deliverers of care through investments in managed care organizations, hospitals became providers of care through offsite clinics, invading the traditional domain of doctors, and physicians took on new risks for the cost and quality of the services they offered by signing preferred or exclusive provide contracts.

In response, the hospitals formed integrated networks seeking access to new markets, economies of scope and scale, and complements to their distinctive competencies. However, as the environmental turbulence continued to increase, the hospitals reacted with hyper-competitive moves actively disrupting previous competitive norms and each other’s competitive advantages. For example, preferred provider networks linked groups of physicians to particular provider hospitals and health plans. This restricted other hospitals’

access to these physicians and spawned a bidding war. Medical staffs that had taken hospitals years to develop were decimated. Overtime, the competitive actions ceased to provide advantage and success and became only a requirement for survival. Smaller players were marginalized as larger, stronger organizations consolidated their control over resources. The region's healthcare system continues to suffer from "huge systemic flaws: Rampant inflation, large numbers of uninsured, uneven and hard to measure quality and uncertain funding" (Rauber, 2005; Selsky, 2007).

In response to the federal changes, Minnesota reconfigured its healthcare industry a decade later. Healthcare providers responded initially in a manner similar to those in California. However, in contrast to California's hospital executives, those in Minnesota viewed themselves as the architects of a new organizational model. Minnesota's executives constructed collaborative networks yielding "win" solutions for many players in the field. While vigorous competition continued, executives were able to anticipate some of the negative effects of their individual competitive actions in the extended field and to create a model of competition that partially controlled for those effects.

In the end, the process of industry restructuring in California generated negative externalities, whereas industry transformation in Minnesota retained negative feedback brakes and avoided some of these effects. As illustrated by these examples, hyper-competition in a turbulent environment can result in unanticipated negative effects. In California, failures to develop sustainable, collective strategies "echo in the form of failed alliances, labor problems and uncertain financial health" (Selsky, 2007), whereas the collaborative efforts of hospitals in Minnesota contributed to a more successful, field-level change.

If successful adaptation in a turbulent environment is best achieved through collaborative effort, it is imperative that such collaboration between field players be fostered. Although comparisons between a competitive business environment and a public agency are not absolute, they can be enlightening. In the field of defense acquisition, there are many players. As in the hospital examples above, an environmental change resulted in a redefinition of the domain and roles, the emergence of new entities and partnerships, and the creation of new processes. If changes to the system lead to "hyper-competitive" behavior among the new players in the acquisition field now facing restructuring and/or between the new and traditional players, unanticipated negative outcomes can be expected.

This suggests that if substantial reorganization and or codification of emergent processes is undertaken, the DoD should consider how to foster collaboration between the newly formed organizations to develop roles and patterns of interaction viewed as "wins" for multiple players in the field. Structural reform should be complemented by efforts to solicit and incorporate inputs from new and traditional field players with a view toward crafting a field solution. Achieving "the hope that, over time, the DoD acquisition community will understand the benefits of the rapid approach—and the countercultural stigma will dissolve" (Gansler, 2009, p. 26) may require active intervention to change perceptions, and at the very least, a thoughtful consideration of how to avoid worsening the problem when making structural changes.

Conclusion

This report describes the preliminary analysis and findings of our study exploring what drives successful organizational adaptation in the context of technology transition and acquisition within the DoD. It is based on our initial collection and analysis of archival and interview data. Our preliminary analysis suggests that ad hoc problem solving may be an undervalued yet broadly practiced skill set within the DoD. We are currently conducting a

second round of targeted interviews designed to illuminate how those in the JCTD office used ad hoc problem solving and organizational routines to field technology solutions. We will use the data to further explore how ad hoc problem solving may be used to support adaptive responses within the DoD acquisition community and to explicate criteria for determining when to rely on ad hoc problem solving versus when to invest in creating dynamic organizational capabilities.

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A Comparative Assessment of the Navy's Future Naval Capabilities (FNC) Process and Joint Staff Capability Gap Assessment Process as Related to Pacific Command's (PACOM) Integrated Priority List Submission

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Abstract

This report presents the results of research and analyses on current and future operational capability gap development and acquisition practices in the United States Navy and the Combatant Commands (COCOMs), as exemplified by Pacific Command (PACOM). Leveraging key stakeholder interviews and using a systems thinking framework known as the Conceptagon (Boardman & Sauser, 2008), we investigated and assessed the Navy's Future Naval Capabilities (FNC) process as well as the Joint Staff (JS) Capability Gap Assessment (CGA) process as it applies to the annual submission of PACOM's Integrated Priority List (IPL) of capability needs. The study approached both processes as systems and identified and explored their critical systemic attributes such as parts, relationships, boundaries, governance mechanisms/structures, key processes, transformations, stakeholders, and missions, to name a few. Based on this assessment, we conducted a structured and systematic comparison of the two processes to identify good practices and favorable dynamics that are likely to reinforce the desired outcome, which—for our purposes—is defined as the resolution of capability gaps and, ultimately, deployment of needed capabilities to the warfighters. In light of this analysis, we present key insights, explore some problem areas, and discuss possible improvements to the said processes.

Summary of Results

The following bulleted list presents the study team's conclusions and key insights, and it is followed by a list of key preliminary considerations for improvement strategies.

Key Insights Into Effective Practices of the FNC Program

- Participatory and binding measures (as exemplified by FNC roundtable and technology transition agreements) create a sense of collective process ownership amongst stakeholders who may otherwise have differing interests. This increases the chance of solution resourcing and development.
- Communicating intended outputs and outcomes relative to the gap development process (as done by FNC in road shows and associated briefing materials) helps to manage stakeholder expectations and inform stakeholder perceptions of success, culminating in improved stakeholder commitment and acceptance of gap development processes and associated fulfillment activities.
- FNC identification and tracking of gap fulfillment measures (e.g., transition statistics) allows the FNC program to adjust in order to improve performance.
- FNC integration of processes that represent the entire lifecycle of a gap (from gap identification through capability deployment to the warfighter) promotes a seamless transition between different phases of the effort, facilitates flow of required information, and provides for continuity of efforts.

How FNC Practices Could Improve the JS CGA/PACOM IPL Process

- The JS CGA/PACOM IPL process could expand its boundary to include solution providers. Existing structures (e.g., Functional Capability Boards [FCBs], supporting working groups) could be used to facilitate formal participation by the acquisition community.
- COCOM organizations could receive feedback on JS disposition of gap information. Formal, accountable, ongoing and two-way communication would facilitate understanding, expectation management, and feedback. The JS could establish formal communication mechanisms to provide updates on gap modifications (i.e., merging similar gaps, capability board adjustments) and outcomes.
- Gap and solution progress statistics, collected in coordination with the acquisition and warfighter communities (currently partially tracked by the JS and accessible through Knowledge Management and Decision Support [KMDS]), could be documented and published periodically (e.g., annually or bi-annually) and could be actively disseminated to COCOMs and briefed at FCBs and Joint Capability Boards (JCBs).
- These outcome-tracking metrics could be used by both JS and COCOM staffs to inform process improvement efforts. The JS process could establish procedures and update instructions and guidance documents to better define roles and responsibilities with metric and process accountability.

Introduction

The Department of Defense's (DoD) annual Integrated Priority List (IPL) process[1] is an integral part of the Joint Staff's (JS) Capability Gap Assessment (CGA) process,[2] which, once published, is one input among many considered by defense acquisition communities. This process, however, may result in a high-priority IPL capability gap(s) receiving lower priority consideration in the military departments' resource allocation and acquisition decisions. By contrast, the Navy's Future Naval Capabilities (FNC) process is considered by both naval and non-naval audiences to be a remarkably responsive and integrated process

[1] The IPL process is intended to address the nine Combatant Commands' Joint warfighting needs through identification and prioritization of operational capability gaps.
[2] Results of the CGA process are published through a Joint Requirements Oversight Council Memorandum (JROCM).

that supports naval warfighter needs. This is further substantiated by the FNC process transition statistics, which demonstrate a record of successfully addressing naval capability gaps through the allocation of resources and establishment of effective schedules for research, development, and acquisition of needed capabilities (Office of Naval Research, 2012).

In this paper, we present a comparative assessment of the Navy's FNC process and the JS CGA/COCOM IPL process as exemplified in the PACOM IPL process. This study acknowledges FNC is an end-to-end process inclusive of solution development and transition, whereas the JS CGA/COCOM IPL process focuses solely on gap identification and assessment with little integration of solution activities. Although this comparison may first appear asymmetric, we compared the processes across similar steps that culminate in the shared milestone of establishing final, prioritized gaps (see Figure 1). Throughout the course of the study, however, it was frequently noted that integrated solution development activities significantly influenced FNC's gap development activities. As will be explained in our conclusions, in FNC, the interaction and mutual feedback between these steps maximizes the process' overall responsiveness to naval warfighters' needs.

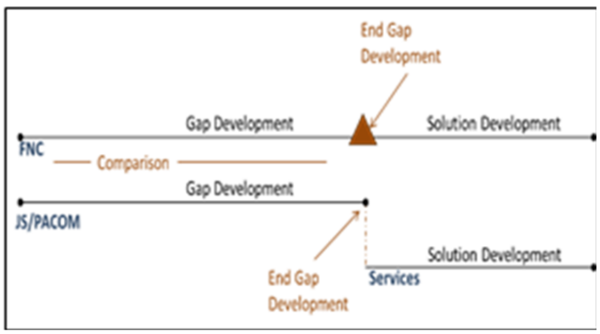

Figure 1. Common Milestones of FNC and JS CGA/IPL

Methodology

A Systems Thinking Approach to Data Compilation & Comparison

The team chose to approach data analysis using a systems thinking approach, which is particularly useful when assessing soft systems, such as enterprises and processes. In this study, the FNC process and the JS CGA/PACOM IPL development process were viewed as systems, each with constituent parts, united by relationships, working together to achieve a specific purpose.

In particular, the team used the soft systems framework, the Conceptagon (Boardman & Sauser, 2008), to assess the FNC process and the JS CGA/ PACOM IPL process. The Conceptagon served as a consistent framework for comparison, standardizing the team's approach to characterizations. It allowed the team to compare seemingly disparate processes across set dimensions of interest. For example, instead of trying to compare the Joint Staff J-8 with the FNC IPT (a difficult comparison at its face value), the team compared across more abstract dimensions such as "actors" and "relationships." Such dimensions of comparison were used throughout the study to facilitate a consistent and coherent approach to identifying the underlying similarities and differences between the two processes.

Data Collection

Data and relevant information for this study were collected through literature review and interviews. To prepare for assessment of FNC, study team members attended the

Office of Naval Research's FNC external training (Office of Naval Research, 2012). This half-day course provided instruction on FNC program basics (FNC goals, objectives, and participants) and key program management processes. In addition to the half-day course, the team conducted interviews with the FNC Program Director (Steve Smolinski) and members of the director's staff. The team also reviewed Integrated Process Team (IPT) charters, FNC briefings, FNC policy memorandums, and related naval instructions. To prepare for assessment of PACOM's IPL, and its movement through the broader Joint Staff CGA process, the team reviewed PACOM documents such as Plans to Resources to Outcomes Process (PROP) briefings. The team also conducted interviews with participants in the PACOM IPL process such as the PACOM science advisor and PROP and future capabilities subject-matter experts. To understand what happens once IPL entries are submitted to the Joint Staff, the team interviewed members of the Joint Staff J-8, Joint Capability Office. The team also reviewed a number of applicable Chairman of the Joint Chiefs of Staff Instructions (CJCSIs). For general awareness, cleared members of the team reviewed additional information, including actual IPL entries.

Research Questions and Study Scope Adjustments

This study's original research question sought to address whether the acquisition process is responsive to COCOM needs by comparing a very responsive system (the Navy's FNC) to the existing JS/COCOM system, using PACOM as an example. To answer this question, the team needed to explore four major research areas: (1) how COCOM needs are identified (collection of warfighter statements of operational shortfalls), (2) how operational shortfalls are captured and communicated (development of the COCOM IPL), (3) how IPL statements are transformed into Joint Capability Gap statements (development of the Joint Capability Gap Assessment), and (4) how Joint Capability Gaps are resolved (Service efforts to fund and develop solutions). While the fourth research area may hold specific statistics that seemingly answer the question, these statistics are subject to great error if the gaps to which the Services are responding, do not accurately reflect COCOM needs. We realized that answering the question was not just a matter of gathering statistics on Service development programs, but also of exploring the gap development process that informs gap resolution efforts. Therefore, we focused on the gap development processes (Areas 1–3) rather than Service solution funding and development (Area 4), which would have been a study in its own right.

In addition to focusing on the gap development process, the study determined focusing on a single COCOM would yield a more detailed analysis. The decision to examine PACOM was made for several reasons: (1) PACOM had a mature gap identification process; (2) PACOM's process is well documented and the team had access to PACOM briefings, instructions, and materials; and (3) the team had personal contacts in the PACOM IPL development process who agreed to participate in interviews.

Limitations of the Study

Due to the decision to focus on a single COCOM, the resulting recommendations may be less applicable to some COCOMs. Also, information used throughout the study was based on access to available documentation and the professional views/perceptions of the individuals interviewed; as a result, some of the information is subject to personal bias and limited to the experience of those interviewed. Finally, to remain unclassified, specific IPL information is not discussed.

Overview of the FNC and Joint Staff CGA/IPL Systems

The following section presents a high-level overview of both FNC and the JS CGA/PACOM IPL processes and provides grounds for understanding the subsequent Conceptagon assessment.

Future Naval Capabilities

Initiated in 2002 (Office of Naval Research, n.d.-b), the FNC program and the associated process addresses naval gaps with science and technology (S&T) solutions on an annual basis (Office of Naval Research, 2012). Using 6.2 (i.e., applied research) and 6.3 (i.e., advanced technology development) funding, this program "develop[s] … quantifiable technology products in response to validated S&T gaps" within a five-year time frame (Office of Naval Research, 2012). Upon maturation of technology and fulfillment of exit criteria (Office of Naval Research, 2012), the FNC program transitions related products to naval acquisition programs of record "for timely incorporation into platforms, weapons, sensors, and process improvements" (U.S. Naval Research Laboratory, n.d.).[3] The FNC process is currently organized along "9 pillars of Enabling Capabilities (ECs)" (Office of Naval Research, 2012), each of which "is an aggregate of science and technology that is aligned to an identified warfighting gap or warfighting capability, and it can deliver a distinct, measurable improvement that contributes to closing the corresponding warfighting gap" (Office of Naval Research, n.d.-a).[4]

The FNC program is managed through a collaborative process. Broadly speaking,[5] OPNAV/HQMC requirements are assessed to identify gaps with S&T solutions. These gaps are then assigned to related pillars for identification of potential solutions. Integrated Product Teams (IPTs) forward prioritized ECs. These ECs are reviewed, assessed, and approved by the Technical Oversight Group (TOG), a three-star Navy and Marine Corps Board of Directors. Related products begin the development phase with strict conditions for an eventual transition to the warfighter as agreed amongst representatives from requirements/resource communities, science and technology developers, and the acquisition community. The overall program is administered by the Office of Naval Research (ONR).

The DoD Joint Staff Capability Gap Assessment/Integrated Priority List Process and Its Employment by Pacific Command

The annual CGA/IPL process produces a prioritized list of DoD warfighting capability gaps that impact DoD Combatant Commands' (COCOMs) execution of operational, contingency, and campaign plans. This process informs the JS CGA, Functional Capability Board (FCB) planning guidance, and development of the Chairman's Program Assessment (CPA), and analyzes baseline resource allocation priorities for the subsequent years' IPLs (K. Carlan, personal communication, April 11, 2012; D. Glenister, personal communication, April 16, 2012).

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[3] The FNC program deals only with products whose technology readiness levels (TRL) are between three and six (Office of Naval Research, 2012).

[4] As explained in the FNC external training (ONR, 2012), EC pillars include sea shield, sea strike, sea basing, FORCEnet, naval expeditionary maneuver warfare, capable manpower, force health protection, enterprise and platform enablers, and power & energy.

[5] The discussion of the FNC process relies on information gathered during FNC Training attended at the ONR on March 9, 2012, and the PowerPoint slides (ONR, 2012) disseminated during the training.

Each COCOM has a different process for generating input into the DoD Joint Staff CGA/IPL[6] process. PACOM's employment of the JS CGA/IPL process is comprised of four fundamental activities, including development, submission, assessment, and validation of capability gaps (K. Carlan, personal communication, April 11, 2012; Carlan, 2011).[7] First, the process begins with the identification, organization, and development by PACOM components and sub-Unified Command organizations of capability gaps through a collaboratively facilitated Plans to Resources to Outcomes Process (PROP) within the PACOM J-8 Resources and Assessment Directorate. USF-J, USFK, USARPAC, PACFLT, MARFORPAC, PACAF, SOCPAC, JIATF-West, JPAC, and ALCOM are the participating PACOM PROP organizations. The PROP results, used for a number of PACOM purposes, including as an input to the IPL, are reviewed and revised by key O-6 level staff officers, J-code Directors, and the PACOM Deputy Commander. Second, the PACOM Commander then prioritizes, approves, and submits the PACOM IPL to the Joint Staff in support of the JS J-8 Force Structure, Resources, and Assessment Directorate CGA process, and informally to the Under Secretary of Defense (Acquisition, Technology, and Logistics; USD[AT&L]). Third, JS J-8 conducts a CGA of all nine COCOM IPLs including PACOM (K. Duffy & D. Glenister, personal communication, April 16, 2012).[8] The assessment process includes review and analysis of IPL capability gaps by nine FCBs, which determine warfighting relevance and result in recommended capability solutions and funding. This process produces and submits a J-8-recommended prioritized list of capability gaps and associated solutions to the Joint Capability Board (JCB). The JCB reviews and recommends the capability gap list to the Joint Requirements Oversight Council (JROC). Fourth, the JROC validates capability gaps, and publishes a JROC Memorandum (JROCM) CGA, which is distributed to the USD(AT&L) and Services for action on capability solutions acquisition and fielding.

The Conceptagon Assessment

The Conceptagon framework (Boardman & Sauser, 2008) aids analysts in conceptualizing and characterizing a system. The framework defines a system's attributes in seven easy-to-remember sets (triplets). This analysis used the Conceptagon triplets. Our understanding of these triplets is explained in the following list:

- *Interior, exterior, boundary*—This triplet describes the perimeter that separates entities that comprise the system, from entities outside the system's control.
- *Wholes, parts, relationships*—This triplet requires identification of the system at hand, the constituent pieces, and the relationships that bind those pieces together.
- *Structure, function, process*—This triplet identifies the key composition, arrangement, or organization (structures) a system employs to support key activities (processes) necessary to produce the desired system behavior (function).

[6] In some cases, the study team refers to the JS CGA/IPL process as opposed to the JS CGA/PACOM IPL process. This change in nomenclature is intended to capture instances wherein discussion points are likely relevant to multiple COCOMs.
[7] All discussion on PACOM IPL activities, including PROP, is based on personal interviews with Kit Carlan and Ken Bruner of PACOM, and PowerPoint slides dated March 23, 2011, and prepared by Kit Carlan.
[8] The information about JS CGA process and details is based on interviews with Air Force Col Keith Duffy of JS and Navy CAPT Dave Glenister of JS.

- *Inputs, outputs, transformations*—This triplet identifies items coming into the system (inputs) and items exiting the system (outputs) as products or deliverables. The triplet also identifies the change (i.e., transformation) that converts inputs to outputs.
- *Command, control, communication*—This triplet explores the system's governance structures and control mechanism, and takes into account communication feedbacks and stovepipes.
- *Openness, hierarchy, emergence*—This triplet investigates a system's ability to accept inputs from the exterior environment and to absorb and accommodate new components (openness), to reconfigure itself in light of new requirements (hierarchy), and to respond to and manage unexpected behaviors produced by such changes (emergence).
- *Variety, harmony, parsimony*—This triplet refers to the system's design balance, assessing if the system has "too much" or "too little" of anything.

Triplet 1: Interior, Exterior Boundary

Navy's FNC Process

There are three pertinent FNC boundaries: program specification, temporal, and stakeholder. The first boundary is established in reference to *program specifications*, which provide that the FNC system works only with 6.2 and 6.3 funding and is only authorized to handle naval gaps with S&T solutions of Technology Readiness Level (TRL) 3 to 6 (Office of Naval Research, 2012). The second boundary defines what is within and beyond the system from a *temporal* angle as portrayed by Figure 2. Accordingly, operational requirements definition takes place prior to the FNC process. As explained in the FNC training provided on March 9, 2012, the process starts with development of S&T gaps by the Chief of Naval Operations and Headquarters, Marine Corps staff and continues as follows: ONR responds to the gaps by proposing ECs, an aggregate of one or more technology products aimed at closing or mitigating these gaps (S. Smolinksi, personal communication, November 29, 2012). Transition of matured S&T products into the acquisition POR is also within the bounds of the FNC program. Integration to the acquisition POR, however, happens subsequent to the FNC process (Office of Naval Research, 2012). Finally, the third boundary defines *stakeholders* who have influence on the FNC system. For example, those stakeholders that actively take part within the FNC process involve IPTs, the TOG, TOG working groups (WGs), resource sponsors, acquisition sponsors, and S&T developers. Some of the passive FNC stakeholders include OPNAV, FCC/MCCDC, naval warfighters, COCOMs, and industry.

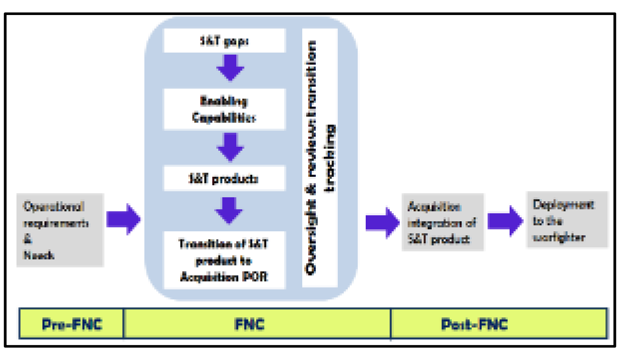

Figure 2. FNC Temporal Boundaries

The FNC boundaries can be characterized as semi-porous, presenting degrees of openness across elements, actors, and issues. Acquisition sponsors, resource sponsors, and S&T developers leverage system flexibility to reach out to and bring in actors from the external environment. This is not to say that the FNC boundaries allow for complete permeability. The program specifications are clear and firm (e.g., non S&T gaps are outside the authorization, budget has a clear mandate) and set structures with clear membership descriptions indicate that membership is not *ad hoc* and does not change over time. The FNC process has well-defined boundaries.

Joint Staff CGA /PACOM IPL Process

When we consider what is within and beyond the JS CGA/ PACOM IPL process, two boundaries appear particularly relevant: conceptual/temporal and stakeholder. According to *the conceptual/temporal boundaries* (Figure 3), PACOM warfighters provide requirements into the PROP process, which generates PACOM capability gaps/shortfalls for the PACOM Deputy Commander's review and assessment (K. Carlan, personal communication, December 10, 2012). The PACOM Commander approves and submits the final PACOM IPL to the JS CGA process. After going through several steps within this process, a JROCM is issued and conveyed to the COCOMs, Services, and OSD offices. The second boundary applicable to the PACOM IPL process is *the stakeholder boundary*. Active stakeholders include the PACOM Commander, PACOM components and J-code Directors, JS Functional Capability Board, JS Joint Capability Board, JROC, and JS J-8 (K. Carlan, personal communication, April 11, 2012; D. Glenister, personal communication, April 16, 2012). Some of the passive stakeholders include other COCOMs, Services, defense agencies, combat support agencies, and inter-agencies. It is important to note that the majority of the Joint Staff CGA/ PACOM IPL process stakeholders interact with but are not necessarily controlled by PACOM.

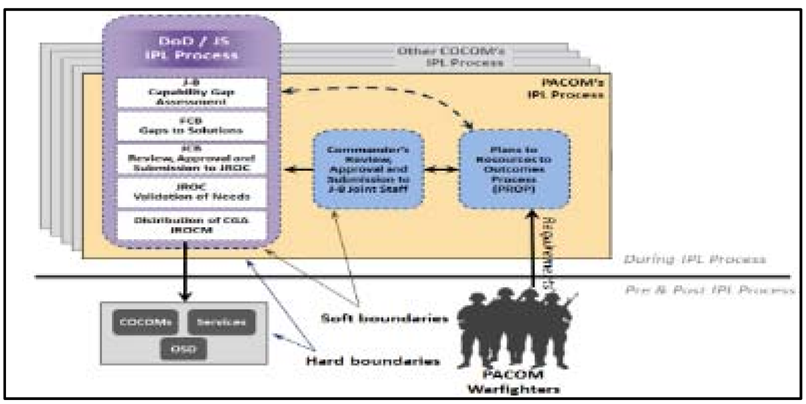

Figure 3. PACOM IPL Process Conceptual/Temporal Boundaries

The JS CGA/PACOM IPL process is characterized by mixed boundaries. The boundary between the PROP process and JS-led CGA process is semi-porous: Although interaction between the PROP and the PACOM Commander is two-way, there are no formally mandated feedbacks subsequent to PACOM's IPL submission (D. Glenister, personal communication, November 26, 2012). PACOM does not control the JS-led CGA process. The outer boundaries of the JS CGA/PACOM IPL process present different levels of openness. At the entry point, the boundary is soft and semi-porous, allowing interaction between the PACOM warfighter and the PROP (K. Carlan, personal communication, April 11, 2012; December 10, 2012). At the exit point, where the JROCM is completed and distributed to COCOMs, Services, and OSD offices, the boundary is hard with no two-way interaction.

Comparative Assessment

A comparison of programmatic boundaries indicates that while the FNC process has clear programmatic boundaries with specific funding lines and approved types of actionable gaps (e.g., naval S&T gaps with solutions at set TRLs); the JS CGA/IPL process does not have an associated type of funding approved/authorized and is expected to address any gap that is deemed significant. Similarly, comparison of the temporal boundary reveals that even though both processes have a three-phase lifecycle (pre, during, and post; see Figures 2 and 3), they differ in system goals. Unlike the FNC system, which is designed to deal with the full gap-to-solution lifecycle, the JS CGA/PACOM IPL process is designed to deal with only capability gaps. Finally, stakeholder boundaries show that the FNC process has a more comprehensive approach to stakeholder participation in line with its full lifecycle process. Unlike the JS CGA/PACOM IPL process, the FNC process includes not only operators but also resourcers and developers. In addition, all FNC stakeholders are bound by both organization (i.e., single naval command) and process, which ensures a unified organizational vision and direct accountability. The JS CGA/PACOM IPL process, on the other hand, predominately involves representatives from the operational communities (with limited input from the acquisition community) who are bound by process. These stakeholders—controlled by multiple command authority—have competing visions and distributed accountability. The nature of the boundaries also impacts the quality of stakeholder communications. Even though both processes have semi-porous boundaries, FNC relies on a collaborative information exchange (i.e., two-way communications) while the JS CGA/PACOM IPL process involves predominantly one-way information delivery.

Key Insights

Consequences resulting from differences in system boundaries of these two processes include the following:

- The FNC process is designed to maximize gap resolution through dedicated programs.
- The JS CGA/IPL system defines gaps but is not equipped to buy, develop, and produce solutions.
- Unified command structure allows the FNC system to centralize control while the JS CGA/PACOM IPL process has distributed and decentralized control.
- Broad program definition (all gaps by all COCOMs) introduces complexity into the JS CGA/PACOM IPL process.
- Collaborative communication enhances shared understanding and expectations amongst FNC stakeholders.

Triplet 2: Wholes, Parts, Relationships

Navy's FNC Process

The FNC system is comprised of its mission, stakeholders, processes, S&T gaps, the S&T budget, S&T products, FNC pillars, Enabling Capability (EC) proposals, and ECs. When these parts and their relationships come together, they form a coherent and meaningful whole—the FNC system. For example, ECs are made up of S&T products, which respond to S&T gaps. Similarly, ECs are organized along the nine FNC pillars.

Analysis of this triplet shows that the FNC process constitutes a well-organized system. Stakeholders have a clear understanding of the parts and the overall system mission. Moreover, the relationships between stakeholders are facilitated by codification of

roles and responsibilities. The parts are also knit together with effective flow of information, resources, and activities. As such, they are configured to form a well-connected whole.

Joint Staff CGA/PACOM IPL Process

The IPL system as a whole is made up of stakeholders, processes, PACOM operational shortfalls, PACOM IPL of capability gaps, and Joint capability gaps. As an example, PACOM components identify and prioritize PACOM operational capability gaps, which are the basis for the PACOM IPL. PACOM IPL capability gaps are then evaluated for and may be incorporated into joint capability gaps.

A key observation from this triplet is that PACOM's IPL development process is dependent on, but does not control, all parts participating in the process. This is significant for two reasons: (1) JS, which does not participate in PACOM's IPL development process, controls the second part of the JS CGA/PACOM IPL process; and (2) Joint capability gap descriptions are affected by other COCOM capability gaps. Analysis of this triplet also sheds light on the flow of information within PACOM's IPL process. While PROP relationships benefit from a collaborative environment, PACOM's PROP to JS relationship is characterized largely through one-way interactions. Additionally, there is limited reporting or feedback on the status of solutions to PACOM's capability gaps; in addition, access to JS tracked information requires that COCOMs pull for information, rather than receive it by way of JS push mechanisms (D. Glenister, personal communications, November 26, 2012).

Comparative Assessments

A comparative assessment of parts within the FNC and JS CGA/PACOM IPL systems shows two discrepancies. First, the FNC process can be characterized as a single system, whereas the JS CGA/PACOM IPL process merges two distinct systems—that is, PROP and CGA (which includes other COCOM gap development processes)—to create a new system. Second, the FNC process identifies, develops, and pursues specific solutions. The JS CGA/IPL process does not involve specifically designated budget and other process parts that target solution (or product) development (K. Carlan, personal communications, April 11, 2012). Solution development is limited to the FCBs' preliminary investigations on potential solution sets.[9] A closer look at these two processes reveals a number of differences in underlying communication approaches. FNC supports feedback relationships that inform participants throughout the process and allow changes, as required. The JS CGA/PACOM IPL process, on the other hand, has limited feedback, generally in the form of a briefing to stakeholders about final Joint gaps, with limited opportunity for follow-on changes. In the case of the JS CGA/ PACOM IPL process this communication approach has three implications: (1) It degrades efforts to maintain continuity of effort and intent from PACOM Commander through the final JS outcome, (2) stakeholders may have limited opportunity to influence outcomes and may not fully understand reasoning behind final decisions, and (3) the ability of the process to self-correct based on process outcomes is limited.

Key Insights

Some of the important consequences of these differences are listed here:

- The JS CGA/PACOM IPL process combines multiple systems and stakeholders, creating a potential for operational strife and inefficiencies. Achieving process integration and cohesiveness requires ongoing, two-way communication, which, currently, is limited.

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[9] The COCOMs list known On Going Efforts (OGE) and recommended actions/solution, and the FCBs request Service input to review and comment on COCOM input and provide their own input.

- FNC solution investigations are more rigorous than those in the JS CGA/PACOM IPL process due to follow-on pursuit of product development.
- Current communication relationships between PACOM, JS, and, ultimately, Services may lead to different (perhaps conflicting) understandings/expectations amongst stakeholders.
- In the JS CGA/ IPL process, current procedures for reporting on solution status may curb shared understanding of how individual COCOM gaps will be resolved.

Triplet 3: Structure, Function, Process

Navy's FNC Process

The intended outcome of the FNC process is to identify and validate an annual list of operational capability gaps and to develop solutions that can be transitioned to a program of record. There are five primary organizational structures that participate in the process: nine IPTs, which are organized along nine FNC pillars; the TOG; a Resource Sponsor; Program Executive Office Systems Command (PEO/SYSCOM); and S&T (Office of Naval Research, 2012). Their configuration and participation is determined according to long-standing FNC procedures and practices. Each organization performs a unique set of roles and responsibilities, producing well-defined information and capability solution deliverables.

The FNC process involves seven functions performed by the aforementioned organizations in the following manner, as explained during FNC training (Office of Naval Research, 2012): Subsequent to the review of operational problems, the nine IPTs develop and forward their top three non-prioritized S&T gaps to the TOG. The TOG reviews and approves the S&T gaps and forwards them to OPNAV. OPNAV officially promulgates and issues the gaps to ONR for development and prioritization of ECs. EC proposals are developed through collaborative discussions with applicable IPTs. Furthermore, Technology Transition Agreements (TTAs), which serve as integral components of the ECs, are developed by EC project managers. The ECs are then forwarded to the IPTs for overall prioritization. The prioritized ECs are reviewed and consolidated by the TOG Working Group and provided to the TOG for approval. The TOG forwards the ECs to the S&T Sponsor who then submits the approved ECs as the Sponsor Program Proposal (SPP) to the Chief of Naval Research for implementation through 6.2 and 6.3 S&T projects. Oversight and review is performed on an ongoing basis through TOG and IPT meetings as well as EC project execution, product development, and the tracking of transition to POR and to the warfighter.

Joint Staff CGA/PACOM IPL Process

The primary intended outcome of the JS CGA/PACOM IPL process is to identify, prioritize, and validate an annual prioritized list of operational capability gaps. It is distributed amongst multiple stakeholders who own different stages of the process. The six primary stakeholders of the process are the PACOM PROP components, PACOM Commander, Joint Staff J-8, FCBs, JCB, and JROC. They are configured and linked according to long-standing Joint Staff and PACOM practices. These organizations operate in a sequential, and at times, interdependent manner to annually assess COCOM capability gaps along with a preliminary review of solutions. Each organization performs a unique set of roles and responsibilities, which can contribute at times to fragmentation between Joint Staff and PACOM stakeholders.

Seven IPL functions are performed by these organizations in the following manner (as confirmed in personal communications; K. Carlan, personal communication, April 11,

2012): The PACOM PROP organizations, which include USF-J, USFK, USARPAC, PACFLT, MARFORPAC, PACAF, SOCPAC, JIATF-West, JPAC, and ALCOM, identify, organize and prioritize their organization's operational capability gaps and shortfalls. Operational officers have responsibility to present and convey their organization's warfighting needs through collaborative data entry and dialogue. Commander's guidance, Defense Readiness Review System (DRRS) deficiencies, mission and associated operational context, operational requirements, and available technology are all examples of informational inputs to the PROP. PACOM J-8 facilitates PROP and performs joint analysis across COCOM missions and operations. It leads the formulation, development, and coordination of the PACOM IPL. Utilizing PROP data along with other current efforts (e.g., Issue Nominations, DDRS deficiencies, rebalance initiatives), PACOM J-8 prepares and submits the recommended IPL to PACOM key O-6 level staff officers, J-Code Directors, and the PACOM Deputy Commander for review, and incorporates feedback in preparation for submission to the PACOM Commander. The IPL is submitted to the PACOM Commander for comment and approval. The approved IPL is submitted to Joint Staff J-8 through the Comprehensive Joint Assessment (CJA). The JS J-8 is responsible for conducting the annual capability gap assessment, which is guided by national military strategy, and informed by IPLs and other warfighting operational needs. The IPL capability gaps are further defined, taking into account similarities and differences across the COCOMs, thereby creating a greater overall number of gaps beyond the top 90 submitted by the nine COCOMs. J-8 selectively distributes the capability gaps to the nine FCBs for review. The FCBs are responsible for assessing and confirming the relevance of the capability gaps and identifying preliminary capability solutions, if known and available. The FCBs facilitate collaborative information exchange across the Services, OSD, non-Service organizations, and COCOMs. FCB results are conveyed to the J-8 through purple slides and quad charts. The JS J-8 develops the recommended list of prioritized capability gaps for review by the JCB. The JCB reviews and establishes the recommended prioritized list of capability gaps with programmatic recommendations and associated military and strategic risk, and submits them to the JROC. The JROC validates the capability gaps for the DoD, and publishes a JROCM CGA, which is then distributed to the USD(AT&L) and Services for capability solutions acquisition and transition to the COCOMs.

Comparative Assessment

Both the FNC and JS CGA/PACOM IPL processes are driven by a number of informational inputs such as warfighting requirements and operational plans. The processes vary in their final outcomes, whereby technology transition to programs of record is the tracked and measured outcome of the FNC process while validated DoD capability gaps are the final outcome of the JS CGA/PACOM IPL process.

Designed for a single Service, the FNC process is a cohesive and well-integrated process. It is employed exclusively through the naval chain of command and the associated procedure. By contrast, the JS CGA/PACOM IPL process is divided along functions executed by the Joint Staff, and multiple COCOM and Service stakeholders, who are guided by varying interests, needs, and resources. As such, process accountability, traceability, and measures of success are inevitably different within each process. FNC activities are comprehensive; FNC represents a "closed-loop" approach to the process, enabling measurable outcomes. In contrast, it is difficult for JS CGA/PACOM IPL stakeholders to quantify how many, and to what degree, gaps are resolved as a result of the JS CGA/IPL process. Furthermore, unlike in the FNC process, in the JS CGA/PACOM IPL process, PACOM capability gaps can lose specificity, be marginalized, or may be disregarded.

Key Insights

Some important consequences of these differences are listed here:

- The way COCOM gaps evolve during the JS CGA/PACOM IPL process results in difficulty tracking program success as capability gaps and capability results are difficult to connect.
- As a solution- and product-driven process, FNC establishes a robust and transparent connection between gaps and solutions, which facilitates tracking program success.
- The JS CGA/IPL process is designed to focus on gap development and validation; as such, it only tangentially addresses gap-to-solution outcomes.
- The hard boundary between capability gap assessment and solutions may limit JS CGA/PACOM IPL stakeholder access to information on program status and results.

Triplet 4: Inputs, Outputs, Transformations

Navy's FNC Process

The FNC process is designed to respond strictly to naval gaps as guided by naval requirements, sources, and mission. Considering all the activities that are taking place within the FNC system, two different transformations are noted: "Requirements to Products" and "Disparate Perspectives to Collective Ownership" (Figure 4). "Requirements to Products" is a systems engineering transformation and, as such, is readily visible with a tangible output. FNC employs a full systems engineering lifecycle, creating a seamless, transparent, and traceable transformation from gap to capability. Transition of enabling capabilities from FNC is tracked from early development activities through delivery to the naval warfighter. In this transformation, requirements are turned into products to be transitioned to Acquisition POR. These products are eventually deployed to the warfighter to resolve a capability gap. Clearly, this transformation is critical for the mission of the FNC program and the broader transformation of requirements to naval capabilities.

The second transformation of "Disparate Perspectives to Collective Ownership" (Figure 4) is perhaps less noticeable but very critical in making the FNC process a successful one. It is concerned with the evolution of attitudes and a culture of commitment amongst disparate stakeholders. The FNC process has institutionalized mechanisms to create a collaborative environment, establish clear roles and responsibilities, and reinforce a culture of collaboration and accountability. Collaborative participation platforms, TTAs, and Transition Commitment Levels (TCLs) all commit stakeholders to clearly and explicitly stated role assignments, transforming functional area biases of requirements/acquisition communities into an integrated viewpoint and a shared mission amongst distinct stakeholders. This collective understanding of responsibility, accountability, and ownership, in turn, enables the "Requirements to Products" transformation referenced previously.

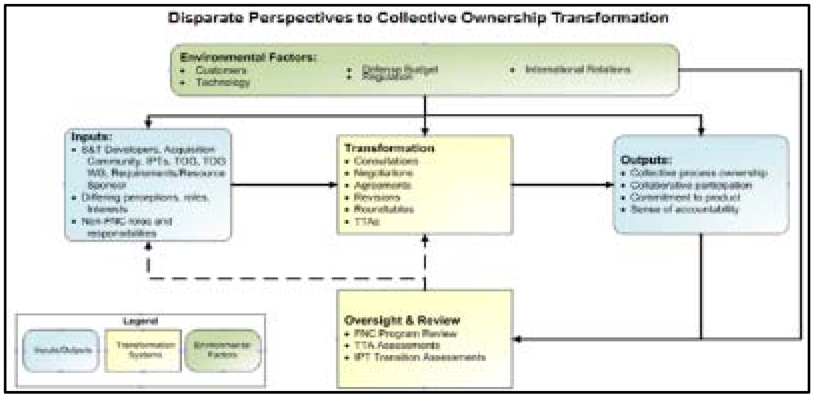

Figure 4. FNC Transformations

Joint Staff CGA/PACOM IPL Process

The JS CGA/PACOM IPL process is designed to consider all COCOMs' needs/gaps, each serving as an input to the JS CGA process. Therefore, diverse COCOM capability gaps (determined by their varying missions) are considered and prioritized.

There are three sequential transformations for gap characterization identified within the JS CGA/PACOM IPL process. The first transformation, "PACOM Requirements to PACOM Gaps," takes place within PROP. Based on PACOM's mission, existing capabilities, available technology, and lessons learned, PACOM components consider PACOM requirements and provide the PACOM Deputy Commander with capability shortfalls/gaps. During the next transformation, "PACOM capability gaps to PACOM IPL," the PACOM Commander evaluates PACOM gaps and issues the final PACOM IPL. Through the third transformation, "PACOM IPL to JROCM CGA," the PACOM IPL is merged with other inputs (e.g., other COCOM IPLs, national military strategy, etc.) to produce joint capability gaps that are identified and prioritized in the JROCM CGA.

The application of this triplet to the JS CGA/PACOM IPL process brings to the fore the fact that out of the three transformations, PACOM controls only the first two, which results in the PACOM IPL. The third transformation is controlled by JS. Since this transformation is designed to integrate and prioritize DoD-wide capability gaps, it takes into account all COCOMs' gaps when producing final capability gap descriptions. As a result, PACOM's IPL is influenced by other COCOMs' capability gaps and their priorities.

Comparative Assessments

As opposed to the FNC system, which is more narrowly focused on naval-only gaps, the JS CGA/PACOM IPL process is designed to address DoD-wide capability needs and consider all COCOM capability gaps. As such, a diverse range of missions, actors, requirements, and procedures feeds into the JS process.

A comparison of the FNC and JS CGA/PACOM IPL process transformations shows that FNC measures of success include not only gap-to-solution considerations but also product transition to warfighter. The JS CGA/PACOM IPL process, on the other hand, does not include a gap-to-solution transformation. Additionally, the JS CGA/PACOM IPL system does not have a formal mandated tracking mechanism linking JROCM outputs to solution outcomes. Another difference between the two processes is that FNC transforms functional area biases of the requirements/acquisition community into a shared understanding and set of collaborative relationships amongst stakeholders. While the JS CGA/PACOM IPL process does leverage working groups and IPTs as consensus building platforms, it does not have

formal and binding agreements for reconciling varying organizational cultures and norms even though it serves a more diverse set of clients and needs.

Key Insights

These differences have several implications for the two processes' performances:

- PACOM capability gap prioritization may be marginalized due to other COCOM higher priority capability gaps. Similarly, PACOM capability gaps may lose theater operational specificity when/if they are merged with other related COCOM capability gaps.
- Due to the impact of multiple COCOM gaps on joint capability gaps, it is difficult to effectively link individual IPL inputs to joint CGA outputs.
- There is limited ability to effectively track and measure the overall transition success in JS-led IPL transformation.
- Cultural transformation in the FNC system enables agreement, shared ownership, and direct accountability.
- FNC outcomes resonate with stakeholders as they produce tangible products as an output.
- By nature of the JS CGA/PACOM IPL process, stakeholder definitions of successful transformation may vary—system transformation may be successful, but it does not mean all stakeholders win.

Triplet 5: Command, Control, Communications

Navy's FNC Process

Command of the FNC process is implemented through ownership and decision-making organizations. The S&T Corporate Board owns responsibility for the FNC program and establishes policy as well as the participating organizations' roles and responsibilities. The nine IPTs, TOG, and Chief of Naval Research (CNR) have decision-making authorities for the execution of the process, production of the S&T gaps, and development and transitioning of the ECs and solutions to the POR for operational use. Control of the process, organizational behaviors, and rules of engagement are built-in mechanisms at both the macro and micro levels. DoD 5000.02 (OUSD[AT&L], 2008), naval requirements, and the nine FNC pillars provide overarching macro control guidance. The TOG Charter, FNC business rules, TTAs (including TRLs and TCLs), project plans, staff training, and transition metrics are micro-level controls to manage and track performance, and support decision-making throughout the process lifecycle.

The FNC process promotes and facilitates formal and informal collaborative information sharing. Closed-loop communications facilitate accountability and provide clear measurable data on outcomes. Information flows through organized coordination and feedback mechanisms with mandatory participation requirements for all stakeholders. Scheduled IPT, TOG, and TOG working group meetings and informal information exchanges enable stakeholders and decision-makers to assess and track key S&T gaps and ECs, and transition capability solutions to the POR for operational use. Dual-hatted IPT co-chairs also facilitate information sharing and general situational awareness through both formal and informal channels as they move between FNC and non-FNC worlds. Documentation of the gaps, ECs, project plans, TTAs, and transition reports are established, maintained, and shared across the FNC organizations.

Joint Staff CGA/PACOM IPL Process

The JS CGA/PACOM IPL process is not owned or governed by a single organization and its stakeholders. The JS owns responsibility for the DoD CGA process, including the joint capability gap assessment and the JROC validation. PACOM is responsible for developing, approving, and submitting the PACOM IPL. The JROC, JCB, JS J-8, and PACOM Commander, have critical decision-making power. As part of their roles and responsibilities, they make decisions to execute the process, and develop and validate capability gaps. FCBs, FCB working groups, and PROP organizations provide prioritized recommendations to the process. There are limited control mechanisms within the JS CGA/PACOM IPL process to facilitate whole-process integration. Formal control is limited due to the absence of such aspects as standard protocols or measures of collective ownership and accountability. The DoD and PACOM level controlling guidance includes Defense Planning and Programming Guidance (DPPG); CJCSI 8501.01A (CJCS, 2004); 3110.01G (released in 2008); 3170.01H (CJCS, 2012); JS guidance on how to compose an IPL; Planning, Programming, Budgeting and Execution System (PPBES); Pacific Theater Strategy (first edition); and PACOM PROP Instruction (Commander, U.S. Pacific Command [USPACOM], 2011).

Communications take place predominantly in the form of one-way information delivery. They are performed through written as well as verbal information exchange mediums. The CGA, IPL, purple slides, quad charts, and JROCM Capability Gap Assessment are classified documents that communicate assessed, prioritized, and validated capability gaps. The JROC, JCB, FCBs and working groups, J-8 Worldwide Conference, and PACOM PROP serve as platforms that enable dialogue and discussions across operational and programmatic representatives.

Comparative Assessment

FNC maintains command of the full lifecycle of the process and the associated decision-making since the governance framework that is in place is holistic, integrated and owned by a single organization. The JS CGA/PACOM IPL process is, on the other hand, governed through multiple separate and independent command structures. PACOM owns its PACOM IPL process as evidenced by the Commander's approval and submission of the IPL. Thereafter, the JS governs the process for the DoD and all COCOMs. FNC is controlled by macro-level USN guidance and policies and a micro view of instructions, as well as roles and responsibilities. The JS CGA/PACOM IPL process relies mainly on macro command level guidance driven by DoD-wide needs and demands.

Both processes provide opportunities for collaboration and coordination. The JS capability gap assessment is, nonetheless, not dependent on COCOM participation. As such, COCOM capability gaps may be marginalized. Further, COCOM participation is informed by real or perceived limited return on time investment. FNC stakeholders have a clear understanding of the FNC lifecycle process and are provided specific updates. COCOMs have diverging perceptions of the process and may be provided more ambiguous information regarding how joint gaps evolve during the cycle and are subsequently fulfilled. FNC offers enhanced accountability through its complete feedback loop that closes the lifecycle of a gap by reporting outcomes to stakeholders. JS CGA/PACOM IPL communications are hindered by logistics, practical process difficulties, and, perhaps most importantly, the potential discrepancy between the gap assessments by COCOMs and the DoD.

Key Insights

These differences between the two processes generate the following implications:

- Centralized and integrated governance and participatory processes that characterize the FNC system provide continuity of process by allowing stakeholder input and agreement throughout the lifecycle of the process and by developing shared understanding, joint ownership, and accountability.
- The distributed governance and one-way communications that characterize the JS CGA/PACOM IPL process disrupt the continuity of the process and provide limited opportunities for management of stakeholder perceptions and resulting expectations.
- As a multi-stakeholder process, the JS CGA/PACOM IPL process may need formal integration mechanisms to bring different parts of the process together for shared ownership and enhanced accountability.
- The absence of formal tracking of gap modification and related outcomes limits JS CGA/PACOM IPL process feedback and creates the potential for missed opportunities in adjusting/correcting performance.

Triplet 6: Openness, Hierarchy, Emergence

Navy FNC Process

The FNC system presents two-way openness throughout its process lifecycle: exterior to interior and interior to exterior. Exterior to interior openness is evidenced by the system's ability to accept evolving naval requirements/gaps, advances/availabilities of technology, new S&T developers, and transition venues/methods. The FNC process is also responsive to data on transition to the warfighter. Interior to exterior openness is presented by the dual-hatted FNC players' ability to cross into non-FNC domains.

There is some evidence of re-configurability of system hierarchy. For example, "the FNC pillars were reduced from 11 to 5 in 2004" (Goldstein, 2006). Similarly, in 2005 the FNC system "was restructured to align with the pillars of the Chief of Naval Operations' and the Commandant of the Marine Corps' vision for the future—Naval Power 21—and to focus on providing Enabling Capabilities to close warfighting gaps" (Office of Naval Research, n.d.-b).[10]

The FNC system accommodates changing circumstances and new process parts; it allows itself to be open to emergent system properties. For example, the transition data influence subsequent FNC processes and performance, which facilitate resource-efficient management of FNC as it permits revision of the process and adjustments in performance based on transition statistics.

Joint Staff CGA/ PACOM IPL Process

The JS CGA/PACOM IPL process is quasi-open and presents mostly one-way openness. Exterior to interior openness of the JS CGA/PACOM IPL process can be seen in its acceptance of evolving requirements and gaps. However, the process is closed to stakeholder feedback subsequent to the issuance of the JROCM. Interior to exterior openness is evidenced by the interior stakeholder communications with the exterior stakeholders.

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[10] This quote can be found on the Office of Naval Research website as cached by December 9, 2012.

The JS CGA/PACOM IPL process has limited options for change as the configuration of system elements appears stable. As a result of limited re-configurability, the system is less versatile and is at risk of critique and perception of ineffectiveness by stakeholders.

Comparative Assessments

Both FNC and JS CGA/PACOM IPL processes present openness, but the JS CGA/PACOM IPL process' openness terminates subsequent to the JROCM conveyance. Another critical distinction between the two processes is concerned with tracking of transition data. The FNC process is responsive to data on transition to the acquisition POR and eventual deployment of the S&T product or capability to the fleet. The JS CGA/PACOM IPL process tracks CGA gaps (i.e., COCOM gaps that are accepted as joint gaps), but does not formally track other aspects of the process (i.e., COCOM gap modification and matching of outcome to original COCOM gap).

Key Insights

Some of the critical consequences that emerge out of the previous discussion include the following:

- Given there is not a mandated feedback system nor a comprehensive transition tracking system in the JS CGA/PACOM IPL process, stakeholders may pursue what they see as unfilled capability gaps through other means such as JCTDs and JUONS, leading to a potential duplication of efforts and inefficient use of resources.
- The FNC process leverages transition data to modify subsequent FNC process and performance. This may result in a more resource-efficient management of the process.

Triplet 7: Variety, Harmony, Parsimony[11]

Navy's FNC Process

The FNC process introduces an instance of harmony in the way it deals with the tracking of S&T products and their delivery to the naval warfighter. To achieve harmony, the FNC process tracks two important transitions. First, the process tracks the transition of S&T products to the intended acquisition POR (Office of Naval Research, 2012). As noted in the boundaries discussion, this transition is an immediate output of the FNC process, and is therefore tracked as a critical success metric. Even so, tracking FNC product transition to the POR does not necessarily provide a complete and accurate assessment of product delivery to the warfighter. For example, the POR itself may never transition to the warfighter due to a number of factors, including program cancellation. Similarly, transitioning products to a POR is not an end in itself; rather it serves a broader purpose. In this regard, tracking only transition to the POR runs the risk of creating a false sense of S&T integration success and is, therefore, too parsimonious of a view. To counter this, FNC leverages variety in transition statistics. In addition to tracking transition to the POR, the FNC program tracks POR transition to the warfighter (Office of Naval Research, 2012). Just as tracking the transition of products to the POR risks creating a false sense of success, tracking only transition of PORs to the warfighter runs the risk of creating an inaccurate assessment of

[11] The triplet of variety, harmony and parsimony is probably the most abstract Conceptagon triplet of all. Rather than identifying every instance of variety and every instance of parsimony, the study team sought to identify instances of harmony, as these were believed to indicate practices that enhanced system performance.

S&T product failure. This is primarily because S&T products are but one of many factors in determining a POR's successful transition. It is the balance of viewing success of direct outputs of the FNC process (S&T product transition to POR) through the lens of broader naval capability delivery (how and if those products are ultimately used by the warfighter) that brings harmony to the FNC program assessments.

Joint Staff CGA/PACOM IPL Process

By nature of its service to multiple stakeholders across all COCOMs, the JS CGA/PACOM IPL process is subject to great variety. An instance of variety is found in the number of number-one priority gaps submitted to the Joint Staff. Herein COCOMs submit their top gaps (through each COCOM's IPL) to the Joint Staff (later forwarded to the JROC) for inclusion in the final CGA. Individual COCOM gaps are ranked in priority order preceding submission to the JS J-8. This process is conducive to producing much variety in the number of incoming number-one priority gaps, as all nine COCOMs submit a gap designated as number-one. The JS J-8 receives the ranked gaps from each of the COCOMs and then works to combine them into a new, consolidated list of prioritized gaps. This consolidation is done so that the DoD can work from a single list of prioritized defense gaps. The process is also used to reduce duplication of gaps and to combine similar gaps. The JS J-8 list is then forwarded through the FCBs and JCB, wherein each group reviews and reorganizes (as required) the list of prioritized gaps prior to final review and approval by the JROC. The passing of the list through many review boards also introduces variety in the process.

Although the processes of combining, accepting, rejecting, realigning, and reorganizing COCOM gaps into a single finalized list of joint capability gaps does introduce parsimony (in the creation of a consolidated list), it does not necessarily bring about harmony. By requesting a ranked list of gaps from individual COCOMs, the process inadvertently sets an expectation that the number-one gaps should all receive top priority in the final list. However this may not be the case as one COCOM's top ten needs may make the final list while another COCOM may not see any of its submitted gaps reflected in the final CGA. Furthermore, the process of homogenizing many seemingly similar gaps into one broad gap statement may create a gap so broad that eventual solutions fail to meet the original need of the submitting COCOM(s). Additionally, variety in the number of reviews as well as groups responsible for approving the CGA fragments the ownership process.

Comparative Assessment

Both FNC and the Joint Staff processes accept gap statements from various groups (IPTs and COCOMs, respectively); however, by consolidating and reprioritizing COCOM-submitted number-one needs, the Joint Staff process may result in stakeholder frustration. The FNC process benefits from a more direct coordination process as opposed to the Joint Staff process where gaps must travel through many working groups and boards. With each change of hands in the Joint Staff process, gaps are further homogenized, refined, and altered. This extended process of shaping capability gaps can result in gaps that, in some cases, only marginally reflect the originally submitted COCOM need.

Key Insights

There are two major consequences and their associated ripple effects resulting from these instances of variety, harmony, and parsimony:

- The FNC process achieves harmony at multiple stages of the process through its organizational structure and continuous planning for final transition to the warfighter.

- Fragmentation of reviewers (through the JS process) and homogenization of COCOM IPLs into joint capability gaps may cause discord leading to general solutions that do not effectively satisfy specific COCOM needs; difficulty in identifying and tracking original COCOM gaps; and COCOMs' resubmission of the same gaps in subsequent years.

Conclusions, Recommendations, and Strategies for Improvements

Admittedly, endstates of the two systems (the naval FNC process and the JS CGA/PACOM IPL process) are markedly different; FNC is a gap-to-solution process (including both gap and solution development phases) whereas the JS CGA/ PACOM IPL process is solely a gap development process. In addition to varying endstates, the systems differ in the breadth of customers they serve. FNC, a naval program serving naval warfighters, is united by purpose, mission, Service, and ownership—in other words, it is an end-to-end by Navy/for Navy process. On the other hand, the JS process serves multiple customers (e.g., COCOMs, Services). As such, while individual COCOM IPL development processes may be united by mission (though not Service), the final disposition of CGA will be subject to a variety of needs across different missions and purposes.

Bearing these differences in mind—particularly as related to varying endstates—we focused our comparison on steps in both processes that lead to a common milestone of final, prioritized gaps. In the course of the comparison, it became evident that FNC's integration of the solution phase better positions the FNC process to leverage inherent feedbacks between the two phases, thereby enhancing its responsiveness to naval needs. Although solution development activities will remain with the Services, our analysis indicates the JS CGA/PACOM IPL process may benefit from strategies employed by the FNC program such as communication and comprehensive gap-to-solution tracking strategies. The team further believes the following recommendations may serve to mitigate some of the frustrations experienced by stakeholders in the JS CGA/PACOM IPL process.

- The JS CGA/PACOM IPL process could expand its boundary to include solution providers. Existing structures (e.g., FCBs, supporting working groups) can be used to facilitate formal participation by the acquisition community.
- The JS could improve transparency relative to gap status. Formal, accountable, ongoing and two-way communication will facilitate understanding, expectation management, and feedback.
- Gap and solution progress statistics, collected in coordination with the acquisition and warfighter communities (currently partially tracked by the JS and accessible through KMDS), could be documented and published periodically (e.g., annually or bi-annually) and could be actively disseminated to COCOMs and briefed at FCBs and JCBs.
- The JS and PACOM should leverage tracking metrics (as recommended above) to inform process improvement efforts. The JS process should establish procedures and better define roles and responsibilities to encourage metric and process accountability.
- The JS can improve stakeholder satisfaction and commitment by promulgating process steps and clarifying guidance documents. The JS should update related Instructions and should consider developing user friendly products and reports that explain the process.

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Enabling Design for Affordability: An Epoch-Era Analysis Approach

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Abstract

Acquiring defense systems in the face of urgent needs, budget challenges, and scarce resources drives the need for designing affordable systems by anticipating uncertain futures and related mission volatility. Despite recent strategies to mandate *designing for affordability as a requirement* in acquisition management, current processes for performing early lifecycle affordability tradeoffs remain underdeveloped. Methods for exploring design tradespaces have matured but have lacked specific focus on evaluating affordability. Affordability tradeoffs have also largely been limited to static tradeoffs of systems in current operating environments, or in single point futures. Given that systems exist in a dynamic and uncertain world, designing for affordability necessitates a method capable of evaluating systems across many possible alternative futures. A new method that leverages both Multi-Attribute Tradespace Exploration and Epoch-Era Analysis is proposed to augment current practices in designing for affordability. This method can be applied to the evaluation of system concepts across multiple epochs (periods of fixed context and needs) and multiple eras (ordered sequences of epochs) and uses the Multi-Attribute Expense metric to provide a measure for aggregate costs and schedule considerations. This paper presents interim research outcomes of an ongoing research project, demonstrating the viability of the approach with a case study.

Motivation

With recent advances in technology and growing demand for enhanced warfighter capabilities, defense acquisition programs have become increasingly complex and costly to manage in the long term. Since the Department of Defense (DoD) is responsible for the research, development, production, and delivery of weapon systems on time and at a reasonable cost, there is an emergent need for the DoD to manage the cost, schedule, and performance of a major weapon system or program that typically runs into billions of dollars within its lifecycle.

With the prospect of slowly growing or flat defense budgets in coming fiscal years (GAO, 2011) and recent budget cuts, the DoD is seeking ways to yield better returns on its weapon system investments and find methods of delivering defense capabilities for less than it has in the past. It is well understood that mitigating uncertainty in estimating cost and schedule parameters that plague the early phases of program formulation would help to identify the true costs of a weapon system or program from the beginning and reduce overruns. This is also in consonance with the advent of capability-based planning, which aims to counter external threats with the best warfighter capabilities deliverable under constrained economic conditions and uncertainty (Patterson, 2012).

Efforts to improve cost and schedule estimation are ongoing, but there has been relatively little progress in addressing uncertainties related to costs stemming from alternative futures that the system may face. The research described in this paper is motivated by this specific aspect in the increasingly urgent need of designing for affordability.

Background

Buying strategies are continuously evolving to place more emphasis on cost in the decision process. With the launch of the Better Buying Power (BBP) initiatives and the Weapon Systems Acquisition Reform Act (WSARA), affordability has been mandated as a requirement at all milestone decision points of program development (Carter, 2010a, 2010b). Designing for affordability is thus imperative to early phase decision-making in the development of weapon systems and programs.

Affordability has become a design requirement due to multiple instances of failure in delivering expected technical performance, increased costs and schedule delays beyond program estimates, and the altering of requirements during program execution (GAO, 2011). The increasing prominence of affordability within the DoD and other working groups has led to the proposal of several notable definitions for the term *affordability*:

(i) The 2010 Carter memorandum defines affordability as "conducting a program at a cost constrained by the maximum resources the Department can allocate for that capability" (Carter, 2010a, 2010b).

(ii) INCOSE defines affordability as "the balance of system performance, cost and schedule constraints over the system life while satisfying mission needs in concert with strategic investment and organizational needs" (INCOSE, 2012).

(iii) NDIA defines affordability as "the practice of ensuring program success through the balancing of system performance (KPPs), total ownership cost, and schedule constraints while satisfying mission needs in concert with long-range investment, and force structure plans of the DOD" (NDIA, 2011).

(iv) The *Defense Acquisition Guidebook* defines affordability as “the degree to which the life-cycle cost of an acquisition program is in consonance with the long-range modernization, force structure and manpower plans of the individual DoD Components, as well as for the Department as a whole” (DoD, 2011).

As evidenced by this set of definitions, the concept of affordability not only incorporates cost but also schedule, performance, lifecycle, and all of these things relative to a larger set of possible investments. An affordable system is thus cost effective on its own—and relative to a larger system investment portfolio—in delivering value to the customer and relevant stakeholders. Affordability is enhanced if the system is capable of satisfying possible changing mission requirements over the system lifecycle. Consequently, a system developed without consideration for affordability is one that has been designed as a point solution in isolation, to meet a specific need at a specific time, possibly requiring the procurement of an entirely new system when customer needs evolve (Bobinis, Haimowitz, Tuttle, & Garrison, 2012).

Since the definitions of affordability also discuss costs relative to allocated budgets, affordability may also be analyzed at various levels of scope, as budgets can be allocated to systems, programs, and even portfolios of programs. Budgets and development timespans allocated to a program or portfolio may be partitioned into smaller packages in many different ways among its constituent systems or programs, respectively.

Affordability at a higher order program level may not necessarily equate to affordability at a lower order constituent system level and vice versa. Therefore, different measures may have to be applied to the design for affordability in an isolated system, program, or portfolio, as well as for the intended cascading of affordability considerations from higher to lower levels of acquisition management.

Higher order levels of affordability analysis will become increasingly important in the future, as they can stimulate an enterprise-driven effort to perform an architectural transformation of traditional engineering design methods that will eventually improve the affordable, full lifecycle operational effectiveness of customer solutions (Bobinis & Herald, 2012).

Past Failures

The consideration of affordability as a requirement during early phase design has become necessary in recent years due to prominent failures in system and overall program delivery. In fiscal year (FY) 2012 (GAO, 2012), nearly half of the DoD’s 96 largest acquisition programs were failing to meet the “Nunn-McCurdy” cost growth and schedule standards that were earlier established to identify troubled programs (Schwartz, 2010, 2013). Despite active reductions in weapon unit quantities and reduced performance expectations, the cost overruns on major defense acquisition programs have grown to more than $300 billion over original program estimates (GAO, 2011).

Notable programs that experienced cost and schedule overruns were the Army’s Comanche armed reconnaissance helicopter, the Navy’s DDG-1000 next-generation surface combatant, and the Air Force’s Transformational Satellite Communications System (TSAT; Cancian, 2010). The Comanche program commenced in 1982, but increasing unit costs resulted in a 10-year delay in schedule and its eventual cancellation in 2004. The $6.9 billion initially allocated for the procurement of 120 Comanche helicopters over five years could have been directed towards upgrading 350 AH-64 attack helicopters to deliver greater warfighter capability but was instead used to purchase 800 other helicopters (Cancian, 2010).

Similarly, the DDG-1000 program was cancelled in 2009 due to high costs and mission limitations, and funds were instead used to procure additional units of the older DDG-51 model. Unnecessary expenditures and schedule delays might have been averted if the Navy initially decided to purchase 13 units of the DDG-51 class for its $23 billion investment in only three DDG-1000 units. TSAT was also cancelled in 2009 due to rising costs and schedule slips. The Air Force might have used the $3.5 billion initial investment in TSAT to purchase seven units of the existing Advanced Extremely High Frequency (AEHF) satellites to avoid gaps in coverage (Cancian, 2010).

These high-profile failures accentuate the urgent need to reduce cost overruns and schedule delays, as well as the need to consider the impact of switching to alternatives later in the lifecycle, in the design of both current and future defense systems, programs, and portfolios. With recent strategies to mandate affordability as a requirement, establishing the preliminary design choice space for the system, program, or portfolio of interest through the generation of many possible alternatives has become imperative to increase insights in early phase decision-making, mitigate the risk of later costly changes, and maximize the value created for the stakeholders (Ross & Hastings, 2005).

Affordability and Tradespaces

The Carter memorandum (Carter, 2010a) stated that “the ability to understand and control future costs from a program’s inception is critical to achieving affordability requirements.” Since cost commitments and uncertainty are usually at their highest levels during early phase design (Blanchard & Fabrycky, 2006), implementing affordability tradeoffs in DoD systems and programs at their points of inception can actively reduce future cost overruns and schedule delays. To perform affordability tradeoffs early in the lifecycle, methods for systems engineering tradeoff analysis are required to demonstrate changes in costs as major decision parameters and time to completion are varied.

The minimization of system cost, while maintaining or increasing system capability across changing contexts over time, motivates the construction of system tradespaces with consideration of temporality. A tradespace is the space spanned by possible design alternatives and is bounded by utility and cost. As the alternatives are generated by enumerating design variables, expanding the tradespace requires a “creative recombination of current resources or systems to create a new system,” which would involve generation of either new design variables or reconfigurations of existing combinations of variables (Ross, Hastings, Warmkessel, & Diller, 2004).

Leveraging the increasing availability of computation power, tradespace exploration is the utility-guided, model-based search for better design solutions by avoiding premature fixation on point designs and narrow requirements (Ross et al., 2004). This allows a deeper and more holistic consideration of capabilities and mission utility instead of being locked too early into requirements and key performance parameters (Neches, Carlini, Graybill, Hummel, & McGrath, 2012).

The use of tradespaces instead of simple tradeoffs of several point designs can lead to better lifecycle results for the system or program of interest. The exploration of tradespaces also enables the promulgation of ilities, which are properties that often manifest and determine value in a system after it is put into use and which have ramifications with respect to time and stakeholders (de Weck, Ross, & Rhodes, 2012).

For example, flexibility allows for leveraging of emergent opportunities and mitigating risks such that the system is able to respond to changing contexts in order to retain or increase value delivery to system stakeholders over time (Viscito & Ross, 2009). As such, flexibility has become a desirable quality in long-lived systems. Due to increasing system

costs and operational lifetimes of systems, various studies have already been conducted to incorporate flexibility into systems during the conceptual design phase (Saleh, Mark, & Jordan, 2009).

For the purposes of this paper, affordability will be a concept that provides explicit considerations for system cost and schedule constraints in value delivery and sustainment to stakeholders. Designing a system or program using affordability tradespaces will thus define its utility or performance space bounded by costs and time. Affordability studies can thus facilitate the attainment of better system, program, or portfolio lifecycle results while meeting budgetary and schedule constraints.

Applying Epoch-Era Analysis to Enable Designing for Affordability

The analysis of affordability tradespaces can become a multifaceted process when the impacts of uncertainties (including risks) inherent in alternative futures are incorporated into conducting tradeoffs during acquisition. To effectively evaluate the impact of dynamic variations in costs with tradeoffs in decision parameters and time to completion, an approach called Epoch-Era Analysis (EEA) can be applied to enhance the design for affordability (Ross, 2006; Ross & Rhodes, 2008).

EEA has been developed to consider and clarify the effects of changing contexts and needs over time on the perceived value of a system in a structured manner (Ross, 2006; Ross & Rhodes, 2008). Instead of discretizing the system lifecycle according to traditional system milestones, EEA discretizes the lifecycle according to impactful changes in the operating environment, stakeholders, or the system itself, through the constructs *epochs* and *eras*.

An epoch is a time period of fixed contexts and needs under which the system operates, and it can be characterized using a set of variables that define any factor, such as technology level and supply availability, which impacts the usage and value of the system. An ordered sequence of epochs constitutes an era and describes the potential progression of contexts and needs over time. Any futures relevant to system performance or costs can be described through assignments to the available epoch variables, providing a form of computational scenario planning (Roberts, Richards, Ross, Rhodes, & Hastings, 2009).

Figure 1 illustrates a notional system trajectory across an ordered sequence of epochs forming an era. In this illustration, the impact of changing contexts can be seen as a downward path on the system as it progresses across time. Rising expectations are also shown, illustrating how the perception of a successful system can be dependent not only on how the system performs within a context but also how that performance compares to changing expectations. In the final epoch of the illustrated era, the system must change in order to meet expectations. In this way, EEA can structure consideration of changing contexts and needs on system success and suggest strategies for how to sustain value in both the short run and the long run.

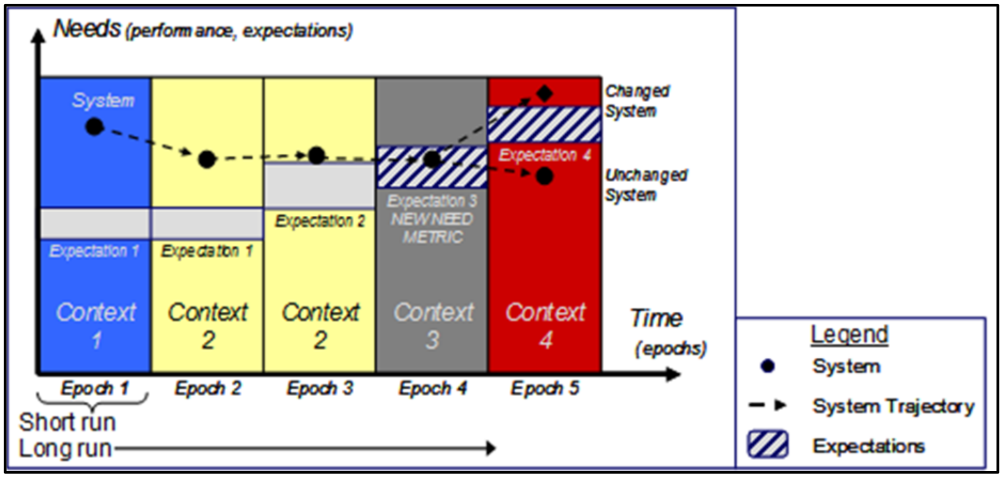

Figure 1. Partitioning Short Run and Long Run Into Epochs and Eras
(Ross & Rhodes, 2008)

EEA can be used with dynamic Multi-Attribute Tradespace Exploration (MATE), a conceptual design method that generates large numbers of designs through combinations of nonlinear functions of their performance attributes and compares their costs and utilities (Ross et al., 2004). Enumeration and evaluation of many alternative designs allow for a more complete exploration of a larger design tradespace. Evaluation of a single point design in which time-dependent performance variables are present can also be performed.

Therefore, the application of EEA to designing for affordability in a system, program, or portfolio can allow analysis of value delivery for single or multiple point designs across multiple epochs and multiple eras. System engineers can thus contribute to realizing better buying power by examining affordable systems previously overlooked or discarded (e.g., more affordable solutions may emerge from previously neglected regions of the tradespace).

Multi-Attribute Expense in Designing for Affordability

Designing for affordability is not only concerned with the monetary lifecycle cost of a system. While many definitions of *affordability* exist, there is general consensus that any evaluation of affordability must include a system's "schedule" of development and its responsiveness to emerging needs (Mallory, 2009; Herald, 2011; INCOSE, 2012). However, such temporal considerations are often difficult or impossible to represent in dollars. Non-monetary measures beyond traditional forms like lifecycle cost are thus required. An additional concern is that dollars for a system are often allocated from different budgets—for example, development versus operations. These different "colors" of money may be allocated (and spent) with differing degrees of ease. Analysis without aggregating these different types of dollar budgets may provide additional insights that would otherwise be lost if dollars were aggregated into a single monetary measure.

A possible measure capable of keeping track of both monetary and non-monetary considerations, as well as keeping different colors of money separate, is the Multi-Attribute Expense (MAE) function, which has previously been used in a satellite system design case study as an independent variable in tradespace exploration to capture both a system's development time and initial operating costs (Diller, 2002). MAE is formulated similarly to a Multi-Attribute Utility (MAU) function (Keeney & Raiffa, 1993). *Expense* refers to aspects of the system design and development that the designer wants to keep at low levels, a concept akin to the notion of negative utility. Expense is principally focused on "what goes into a

system," in contrast to utility, which is focused on "what comes out of a system." Typically quantified on a zero to one scale, where an expense level of one denotes complete dissatisfaction and an expense level of zero denotes minimal dissatisfaction. As such, a stakeholder typically demands maximal utility and minimal expense in an ideal design (Nickel, 2010).

An MAE function requires careful construction through stakeholder interviews to elicit informed responses and aggregate preferences to capture articulated value. Because MAE is a dimensionless, non-ratio scale metric, an entity with twice the MAE number over another does not imply that it is twice as expensive in terms of monetary value.

Since temporal elements like schedule constraints and time-to-build have extensive leverage on the different colors of money, the MAE can be extended to affordability applications in federal acquisition processes. Instead of comparing monetary costs against utility, EEA can be modified to compare MAE against MAU in order to perform affordability-driven analysis that captures the elements of both time and costs.

A method that leverages the EEA approach and MAE metric can allow for the effective comparison of benefits and costs across a range of alternative futures. Also, this method may transform traditional engineering practices in acquisition management if it is able to account for system changes due to shifts and perturbations, manage lifecycle differences between subsystem or subprogram components, evaluate feedback, and be adaptive to evolving system behaviors (Bobinis et al., 2012). Since affordability is a concept evaluated over time, such a method can provide structured options for improvement to enable enhanced design for affordability.

Proposed Method Based Upon Epoch-Era Analysis

A new method that leverages the EEA approach and MAE metric is proposed to help enable the design of affordable systems, allowing for the structured evaluation of design alternatives across many alternative futures and helping to ensure that a potential design's cost is acceptable across the entire lifecycle. The proposed method is inspired by the Responsive Systems Comparison (RSC) method, which was developed earlier to support designing for changeability (Ross et al., 2008). RSC is a prescriptive operationalization of MATE and EEA. RSC has been previously applied to the design of a satellite radar system (Ross, McManus, Rhodes, Hastings, & Long, 2009).

RSC is designed to "guide the … practitioner through the steps of determining how a system will deliver value, brainstorming solution concepts, identifying variances in contexts and needs (epochs) that may alter the perceived value delivered by the system concepts, evaluating key system tradeoffs across varying epochs (eras) to be encountered by the system, and lastly developing strategies for how a designer might develop and transition a particular system concept through and in response to these varying epochs" (Ross et al., 2008). It is hypothesized that through modifying several original processes in RSC, incorporating recent refinements to EEA, and utilizing MAE to better capture the diversity of expenditures on a given system, the proposed method can more effectively address the time and resource-centric approach of designing for affordability.

Overview of Proposed Method

The overall structure of the proposed method consists of nine processes, which are grouped into three distinct parts: information gathering (Processes 1 through 3), alternatives evaluation (Process 4), and alternatives analysis (Processes 5 through 9). A graphical representation of the method is shown in Figure 2. The information-gathering portion, Processes 1 through 3, consists of defining the context and problem statement,

stakeholders and respective needs, and contextual variables. The alternatives analysis portion, Processes 5 through 9, compares the dynamic properties of potential designs across the potential futures that the system may encounter. These two main portions of the proposed method are bridged by Process 4 (Design-Epoch Tradespaces Evaluation), which can provide feedback to decision-makers and stakeholders, creating an opportunity to revisit the information-gathering processes. Process 4 also provides cursory analysis of potential designs in preparation for the more in-depth alternatives analysis in the second half of the method.

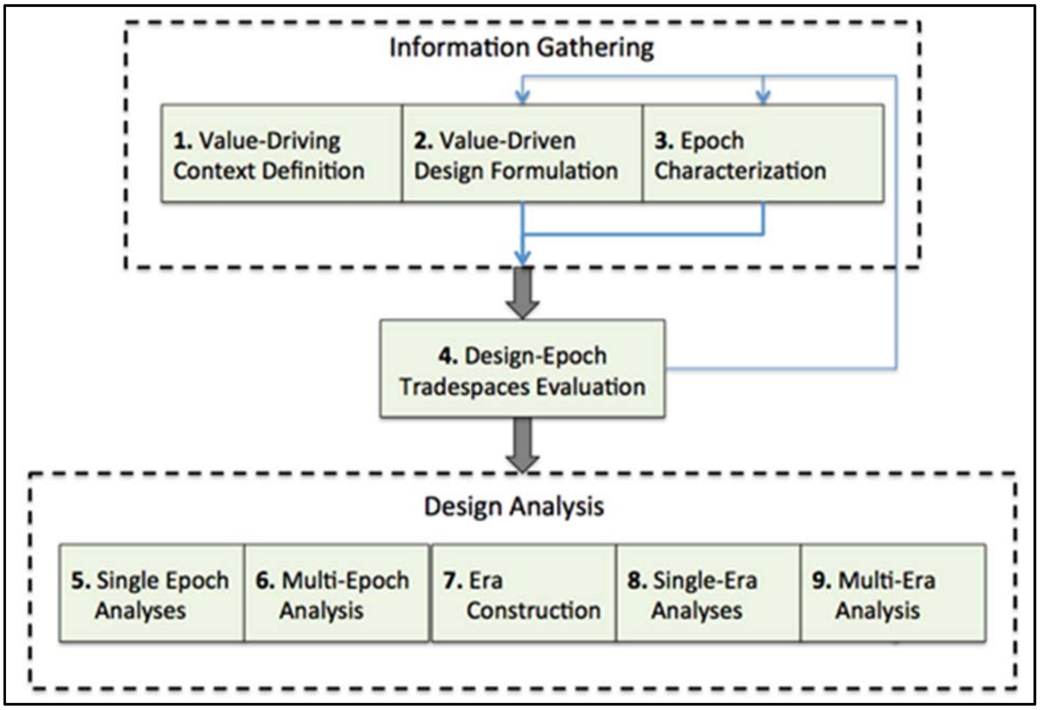

Figure 2. A Graphical Overview of the Gather-Evaluate-Analyze Structure of the Method

The processes of the proposed method, with brief descriptions of the activities involved, are as follows, with modifications to the prior RSC method emphasized (in italics):

Process 1: *Value-Driving Context Definition*

The first process of the proposed method involves development of the basic problem statement. The stakeholders are identified, relevant exogenous uncertainties are elicited, and an initial value proposition is formed. *The resources available to each stakeholder are examined along with the associated uncertainties.*

Process 2: *Value-Driven Design Formulation*

The second process begins by defining the needs statements for all stakeholders, which become the attributes of system performance, along with utility functions describing each stakeholder's preference for each attribute. *The stakeholder resources statements are also elicited (with corresponding expense functions), which then become the attributes of the system's expense function.* The system solution concepts are proposed from past concepts or expert opinions. These concepts are decomposed into design variables of the system.

Process 3: *Epoch Characterization*

In this process, the key contextual uncertainties are parameterized as epoch variables, and possible future contexts are identified. Uncertainties in stakeholder needs are elicited*. Uncertainties in resource supply and availability are also identified, along with changes to stakeholder preferences on resource usage*.

Process 4: *Design-Epoch Tradespaces Evaluation*

This process utilizes modeling and simulation to map the design and epoch variables to system performance attributes *and expense attributes*. Stakeholders' utility *and expense* functions are then used to generate the MAU *and the MAE* for each design, within each epoch.

Process 5: *Single Epoch Analyses*

This process includes the analysis of MAU *and MAE* of alternatives within particular epochs, including designs graphically compared on an MAU versus MAE scatterplot for any given epoch (time period of fixed operating context and stakeholder needs). Within-epoch metrics, such as yield, give an indication of the difficulty of a particular context and needs set for considered designs.

Process 6: *Multi-Epoch Analysis*

After completing the traditional tradespace exploration activities of Process 5, in which the practitioner compares potential designs within a particular epoch, metrics are derived from measuring design properties across multiple (or all) epochs to give insight into the impact of uncertainties on potential designs, including the evaluation of short run passive and active strategies for affordability (i.e., efficient MAU at MAE*). In addition, resource usage can be analyzed to identify designs that are robust to the factors identified in Process 3 (e.g., decreasing budgets or labor availability).*

Process 7: *Era Construction*

This process constructs multiple sequences of various fixed duration epochs together to create alternative eras, which are long-term descriptions of possible futures for the system, its context, and stakeholder needs. This process can be performed with the aid of expert opinion, probabilistic models (e.g., Monte Carlo or Markov models), and scenarios of interest to stakeholders.

Process 8: *Single-Era Analyses*

This process examines the time-dependent effects of an unfolding sequence of future epochs created in Process 7. By examining a particular series of epochs for a given length of time, decision-makers can identify potential strengths and weaknesses of a design and better understand the *potential impact of path-dependent, long-run strategies for affordability.*

Process 9: *Multi-Era Analysis*

This process extends Process 8 by evaluating the dynamic properties of a system across many possible future eras, *identifying patterns of strategies that enable affordability across uncertain long-run scenarios.*

In the remainder of the paper, the first three processes are described in more detail for the purposes of the demonstration case (as of the date of this paper), with the modeling and simulation and the analysis processes to be applied later in the ongoing effort.

Offshore Patrol Cutter Acquisition Demonstration Case

The case chosen for an initial demonstration of the proposed method is drawn from Schofield (2010), who described an $8 billion Coast Guard Offshore Patrol Cutter (OPC) acquisition program for over 20 ships, each with a service life of around 30 years. For this paper, only the acquisition of one ship will be considered, and the alternatives will be limited to a few point designs rather than an exhaustive tradespace of alternative designs. A brief description of the project is given. Ongoing work will extend the analysis to the program level to examine measures of affordability on multi-year and multi-unit acquisitions.

The OPC operates in a variety of areas to perform many different missions, including ports, waterways, and coastal security (PWCS), search and rescue (SAR), drug interdiction (DRUG), migrant interdiction (AMIO), living marine resources (LMR), other law enforcement (OLE), and defense readiness (DR; Fabling, 2010). These mission areas include autonomous operations as well as cooperative missions with other vessels, requiring endurance and maneuverability, respectively.

Process 1: *OPC Value-Driving Context Definition*

The value-driving context for the OPC is made up of the value propositions as well as the key stakeholders involved in decision-making and funding. The basic stakeholder relationships present for the OPC system are depicted in Figure 3. As shown in the figure, the internal stakeholders are the entities between which the primary exchanges of value occur.

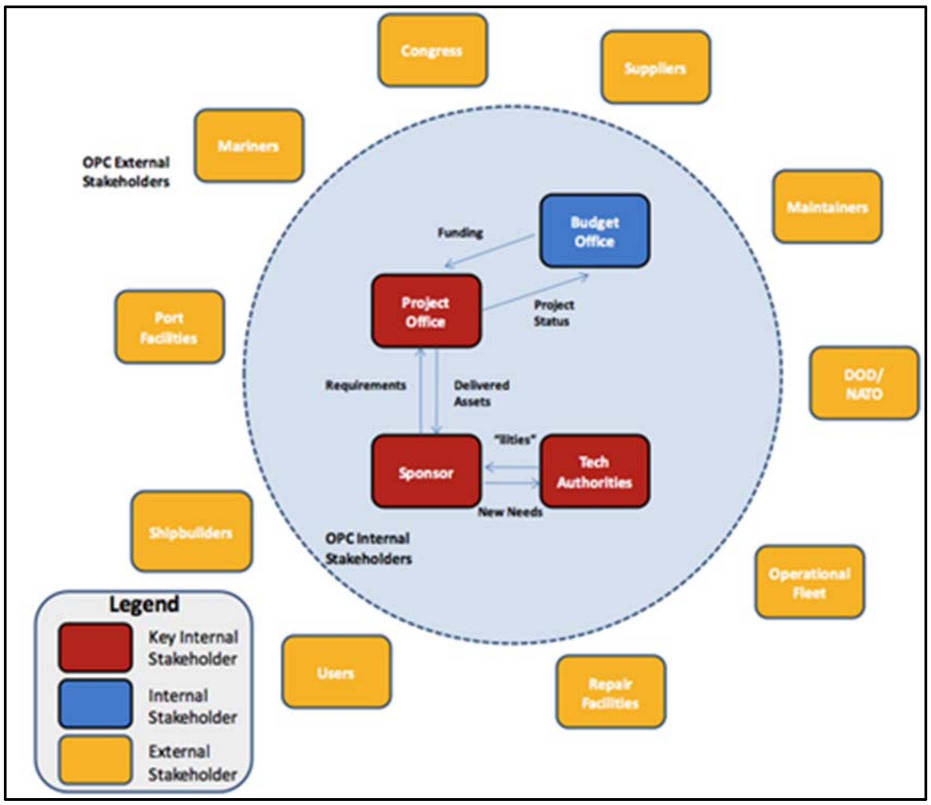

Figure 3. A Graphical Deptiction of the Stakeholders and Their Relationships in the OPC System
(Schofield, 2010)

Schofield (2010) defined the value propositions for each stakeholder as follows:

> **Project Office:** Provide a new cutter fleet meeting operational requirements within a defined budget level and delivery to coincide with decommissioning of current WMEC fleet.
>
> **Sponsor:** Develop operational requirements that meet the mission needs of the Coast Guard and Coast Guard user requirements.
>
> **Technical Authorities:** Ensure new developed system meets legacy, external constraints, and design standards with technologies that maximize capability within established risk requirements. (p. 82)

It is clear from the value propositions that concern for resource usage is not consistent across stakeholders; as one might expect, each stakeholder has different expectations and goals with regard to resources involved in the project. The Project Office specifically addresses two standard resources: budget (“defined budget level”) and schedule (“delivery to coincide with ...”). The Sponsor appears to be primarily concerned with the mission needs and user requirements of the organization, and resource usage is not of primary concern. The Technical Authorities’ value statement includes the aspect of technological resources that enable core capabilities. In the second process of the proposed method, interviews of each stakeholder will better reveal their preferences on the usage of the resources with which they are concerned.

Process 2: *Value-Driven Design Formulation*

The second process builds upon the initial system context definition by first proposing the system design concept and then eliciting the performance attributes desired by the stakeholders. The design concepts are then partitioned into potential design variables for the proposed system. To better identify the key design drivers, the relationships of design variables to performance attributes are then assessed qualitatively by the values “none,” “low,” “medium,” or “high” impact, using a Design-Value Matrix (DVM) as a visual aid for this activity. Schofield (2010) decomposed the value propositions generated in Process 1 to infer the performance attributes and then map them to the design variables of the system.

For the present study, a new matrix is created to map the impact of design variables to the resource expenditures of the system, qualitatively assessing each design variable’s impact on each expense attribute. In this way, an alternative DVM can be generated, focused on expense attributes, and is shown in Figure 4 with purely notional data. By summing the rows and columns, the practitioner can quickly determine which design variables have the most impact on general resource usage (in the notional example, the length and propulsion type are the most impactful), as well as which resources are more sensitive to the present design choices (again, from the notional data, the Operations Cost is the most sensitive, followed by Blue Money and Acquisition Cost). Generating an enhanced DVM, with both utility attributes and expense attributes, provides an expanded cost and benefit perspective on the ramifications of various design decisions.

Expense-Focused DVM (Notional Values)							
Key Internal Stakeholder: Sponsor							
Expense Attributes / **Design Variables**	Length (ft)	Power (hp)	Propulsion Type (Diesel, CODOG, CODAG, Turbo)	Antennae Space (cub. Ft)	Crew size (#)	...	**Total Impact**
Acquisition Cost	9	3	3	3	1	...	**24**
Operations Cost	9	3	9	1	9	...	**32**
Acq. Schedule	1	1	3	1	0	...	**15**
Red Money	3	1	1	9	1	...	**19**
Blue Money	9	3	9	3	1	...	**25**
Total	31	11	25	17	12	...	

Figure 4. A Design-Value Matrix Reflecting the Notional Impact of Design Variables on System Expense Attributes

Process 3: *Epoch Characterization*

After identification of the design variables, performance and expense attributes, and their corresponding relationships, the internal and external uncertainties are added into the analysis. The prior study (Schofield, 2010) listed the external uncertainties (in the associated categories) related to the OPC as follows:

> **Technology:** VUAV integration; major C4ISR system upgrade; and new and more capable (size, range, personnel carried) small boats.
>
> **Policy:** Marine engine emission reductions; reduced copper content from shipboard systems (sea water systems); increased intelligence gathering into government-wide system.
>
> **Budget:** Loss of acquisition budget prior to IOC; increase in operational funding for increased operational usage.
>
> **Systems of Systems:** Deploying with National Security Cutters; new cutter-deployed helicopters.
>
> **Missions:** Support of arctic region for fisheries; adding environmental cleanup response capability; more frequent international presence particularly for peacekeeping missions. (p. 93)

Epoch variables are generated from these uncertainties by determining the primary source of the possible changes in operating context. For instance, Schofield (2010) used the marine engine emission reductions uncertainty in the Policy category to generate the “Engine Emissions Rating” epoch variable, which has an integer value range from 2 to 4. Once each epoch variable is created, the impact of the epoch variables on each of the design variables, performance attributes, and resource attributes can then be depicted with an Epoch Descriptor Impact Matrix, similar to the DVM in Process 2. An example Epoch Descriptor Impact Matrix with notional values is shown in Figure 5.

Epoch Descriptor Impact Matrix

Epoch Variables	VUAV	C4ISR Racks	Small Boat Size	Engine Emissions	SCIF Size	…	**Total Impact**
Design Variables							
Length (ft)	1	9	3	1	3	…	**47**
Power (hp)	1	3	9	1	3	…	**54**
… …	…	…	…	…	…	…	**…**
Total	**15**	**24**	**32**	**31**	**29**	**…**	
Utility Attributes							
Air Cap	9	1	0	3	3	…	**31**
Range	1	3	9	1	9	…	**43**
… …	…	…	…	…	…	…	**…**
Total	**27**	**23**	**28**	**21**	**32**	**…**	
Expense Attributes							
Acq. Schedule	1	1	3	1	0	…	**25**
Red Money	3	1	1	9	1	…	**39**
Blue Money	9	3	9	3	1	…	**45**
Total	**24**	**21**	**18**	**20**	**16**	**…**	

Figure 5. A Matrix Reflecting the Notional Impact of Epoch Variables on Design Variables, Utility Attributes, and Expense Attributes

Similar conclusions can be drawn as in Process 2; for example, it is clear from the sums of rows in Design Variables that Power is the variable most impacted in general by all uncertainties. Likewise, Range is the performance attribute most impacted by the uncertainties, and Blue Money is the most impacted expense attribute. Conversely, the Small Boat Size epoch variable (with Engine Emissions not far behind) is the most impactful on all design variables, the SCIF Size is most impactful on the utility attributes, and the VUAV is most impactful on the expense attributes. Gaining an understanding of these relationships early in the design process allows the practitioner to begin considering how a design should be oriented to cope with uncertainties as well as to keep in mind those contexts which are especially detrimental to the utility or expense of the system, whether directly or through opportunity costs.

Next Steps: *Processes 4–9*

The study is continuing beyond this paper with the application of the second half of the proposed method. Process 4, the Design-Epoch Tradespaces Evaluation, will use the information generated thus far to calculate the expense measurements for each design, allowing a partial tradespace to be shown on a standard utility-versus-expense scatterplot. Preliminary results can be shown to stakeholders and decision-makers, allowing feedback to Processes 2 and 3, if necessary, to update the design variables and epoch variables under consideration (see Figure 2). Upon completion of Process 4 and any necessary iteration, Process 5 (Single-Epoch Analyses) will then begin to look at the designs' relative resource utilization in different epochs, allowing the practitioner to begin understanding the dynamic

expense properties of each alternative under consideration as well as to pick relevant *point futures* in which to compare alternative designs.

The application will continue with the Multi-Epoch Analysis of Process 6, measuring the designs' expenses across all relevant epochs. Established metrics such as the Fuzzy Pareto Number, Filtered Outdegree, and others will be calculated to help identify designs that are insensitive to the impact of uncertain operating environments and missions (Fitzgerald & Ross, 2012a). Multi-epoch affordability metrics will also be introduced to help identify and rank designs based on resource usage, including those which best adapt to decreasing budgets, those which do not vary widely in resource usage, and those which can best capitalize on increasing technology and spending levels.

In addition to observing design properties across many alternative point futures, it is also informative to analyze design properties through the long run using an ordered sequence of different epochs (i.e., an era). A particular era can be created by combining epochs through expert opinion, random generation, and other means. During Process 7 (Era Construction), one or more of these methods will be used to generate and name possible eras for the OPC. In Process 8 (Single-Era Analyses), metrics of the alternative designs will then be compared for a given era as an indication of design resource usage in one possible long-run future, potentially revealing the path-dependent sensitivity of a particular design (Fitzgerald & Ross, 2012b). This analysis will be broadened to identify patterns across multiple possible long-run epoch sequences in Process 9, Multi-Era Analysis, wherein further insights into the long-term resource behavior of the OPC under many different scenarios will be gained. These insights will be aided through the application of existing and proposed metrics to compare properties such as the stability of operating costs, stability of manpower requirements, and adaptation to budget variation.

Discussion

Designing for affordability throughout the acquisition process, but especially in the early phases, can expedite significant reductions in cost and risk and enable the value delivery of either effective systems or programs within economically frugal and risk-averse environments. By applying the proposed method to a demonstration study, we intend to illustrate how affordable solutions within fluid tradespaces can be identified in a systematic and informed manner, accounting for changing sets of mission requirements, operating contexts, and available budgets.

As the preceding demonstration begins to illustrate the application of affordability considerations to a single acquisition program, the same method can also be applied at the levels of systems, programs, and portfolios of programs. Introducing different levels of scope to affordability studies necessitates clear distinctions among systems, programs, and portfolios in future work.

For the purposes of the current discussion, the distinction between system, project, and program is now described. A system is typically defined to be a combination of interacting elements organized to achieve one or more stated purposes (INCOSE, 2012), whereas a project can be defined as the enveloping process that encompasses the socioeconomic and technical considerations in delivering the system. A program can be defined as a group of related and interdependent projects managed together to obtain specific benefits and controls that would likely not occur if these projects were managed individually (KLR, 2008).

Program-level affordability can be achieved through either a top-down or bottom-up approach. A top-down approach entails the application of affordability considerations at the program level such that its effects potentially cascade down to its constituent systems. A

bottom-up approach conversely demands the aggregation of system-level affordability for each constituent system in order to establish program-level affordability. These two approaches may not yield the same results, and it is an avenue worth exploring to determine the more effective or viable option.

Another paradigm for exploration is that of portfolio-level affordability. A portfolio can be defined as a collection of projects or programs grouped together to facilitate the effective management of efforts to meet strategic business objectives (KLR, 2008). These projects or programs are not necessarily interdependent or directly related. Portfolio-level affordability analysis may involve applying affordability considerations across multiple projects, programs, and possibly even portfolios. Given that the DoD has been evaluating the expenditures for both defense acquisition programs and portfolios, a portfolio-level affordability study can provide overarching guidance to architecting entire defense capabilities within realistic bounds of cost and time. Similarly, top-down and bottom-up approaches can also be taken to achieve portfolio-level affordability.

Quantitative measures of cost, schedule, and performance can also be derived at system, program, and portfolio levels to serve as vital health indicators at different tiers of acquisition processes. By assessing the performance of an individual system or program as well as entire defense portfolios, the return on investment that the current defense acquisition system delivers to stakeholders can be accurately measured and analyzed. Systems, programs, and portfolios can then be individually or collectively calibrated based on a multitude of affordability indicators in order to fulfill evolving cost and schedule constraints.

As a starting point, affordability requirements have already been mandated at current program milestone reviews and at the inception of new programs in consonance with the Carter memorandum. Designing for affordability can be extended to all levels in acquisition management in order to ensure that value delivery in systems, programs, and portfolios can be sustained. The method described in this paper could potentially be used to gain insights at each of these levels of acquisition management.

Another avenue for study is the concurrent application of affordability with other ility considerations. Research on the tradeoffs for changeability (Fitzgerald & Ross, 2012b), survivability (Richards, Ross, Hastings, & Rhodes, 2009), and evolvability (Beesemyer, Fulcoly, Ross, & Rhodes, 2011) in previous case studies may possibly be repeated with affordability considerations, and results may yield “affordably changeable,” “affordably survivable,” or “affordably evolvable” systems that were previously overlooked or discarded. For such change-related ilities, existing methods such as the Epoch Syncopation Framework (ESF) can also be utilized to account for cost, performance, schedule, and uncertainty factors regarding experienced epoch shifts in the analysis of design tradespaces (Fulcoly, Ross, & Rhodes, 2012). This can promote the development of rules and strategies to execute change mechanisms with explicit considerations for cost and time across a system lifespan.

Conclusion

Current strategies to mandate designing for affordability as a requirement in acquisition management are still at their infancy stages. A particularly challenging aspect of designing for affordability is to make decisions not only for today’s mission and operating context but also for alternative futures where budgets and missions may change and contexts may shift. We propose a method that can enable practitioners to design for affordability in a more effective and comprehensive manner, given this challenge of a dynamic world. By leveraging the EEA approach and the MAE metric, tradespaces

containing many possible design alternatives can be explored with stronger considerations of aggregated costs, time, and performance in order to focus specifically on evaluating affordability. This will facilitate the conduct of affordability tradeoffs in dynamic operating environments with many possible alternative futures and eliminate design restrictions to only single point futures. The viability of this method has been preliminarily demonstrated with the OPC acquisition case study. It will be further elaborated in the course of ongoing research. Inspired by the existing Responsive Systems Comparison method, this method places increased emphasis on tradeoffs important to managing changes in available and expended resources over time. It is anticipated that the method could be applied to ascending levels of acquisition considerations, from systems to programs to portfolios. Program-level affordability analysis might consider the acquisition management of the entire OPC acquisition program for over 20 ships, while portfolio-level affordability analysis might entail the concurrent acquisition management of the OPC program with other related or unrelated naval programs. With this method, the concept of affordability may be considered simultaneously with other ilities, providing synergistic insights from other existing methods such as the ESF to enhance the design of affordable systems. Based on early results, the method appears to show promise as an enabler for better design for affordability in systems, programs, and portfolios in the future.

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Measuring Dynamic Knowledge and Performance at the Tactical Edges of Organizations: Assessing Acquisition Workforce Quality

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Abstract

The efficacy of defense acquisition is highly dependent on acquisition workforce (AWF) quality, but assessing such quality remains a major challenge, particularly given the knowledge-intensive and dynamic nature of acquisition organizations and processes. Hence, it is difficult to gauge—much less predict—the impact of leadership interventions in terms of policy, process, regulation, organization, education, training, or like approaches. Building upon the development and application of Knowledge Flow Theory over the past couple of decades, we have developed a state-of-the-art approach that enables us to analyze, visualize, and measure dynamic knowledge and performance. The main idea is to apply this approach inwardly to measure the dynamic knowledge and performance of acquisition processes (e.g., within contracting and project management organizations), but we also look outwardly (e.g., at warfare processes at the tactical edges of military combat organizations) to conceptualize an operational proxy for acquisition workforce quality: *end customer performance*. This proxy offers its best potential to complement, not replace, other metrics in use, development, and conceptualization today, but it arguably concentrates on one of the most important AWF quality determinants: how acquired systems affect operational performance.

Introduction

Acquisition is big business. The DoD alone routinely executes 12-figure budgets for research, development, procurement, and support of weapon systems and other military products and services (Dillard & Nissen, 2005). Acquisition is also a knowledge-intensive business. In addition to myriad laws governing federal acquisition in the U.S., a plethora of rules and regulations specify—often in great detail—how to accomplish the planning, review, execution, and oversight of defense acquisition programs, large and small, sole-source and competitive, military and commercial (Dillard, 2003).

As a result in part—and due to high complexity, multiple stakeholders, goal incongruence, open process execution, and large pecuniary rewards for some participants—acquisition has been a problematic business too. Seemingly every decade, acquisition problems must be addressed by another Blue Ribbon panel and reformed yet again. The Better Buying Power Initiatives (BBPI), as a recent instance, mandate efficiency and productivity improvements in five acquisition business areas: (1) affordability and cost growth, (2) productivity and innovation in industry, (3) competition, (4) tradecraft in services acquisition, and (5) non-productive processes and bureaucracy (Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics [OUSD(AT&L)], 2010). These initiatives focus principally on incentives for and interactions with contractors. The Defense Acquisition Workforce Improvement Act (DAWIA), as another instance, was signed

into law in 1990 and emphasizes the education, training, and certification of people in the acquisition workforce (AWF). Of course, the two leadership interventions are related: people in the AWF need to know how to effect the kinds of efficiency and productivity improvements mandated via the BBPI.

These characteristics of acquisition emphasize the criticality of quality in the AWF itself: With so much at stake, and in such a knowledge-intensive environment, a high-quality workforce is essential to competent and professional acquisition performance.

These characteristics also elucidate the central role played by people and organizations in the AWF. People must be knowledgeable and work effectively—both in terms of their own professional acquisition activities and with many others in acquisition and customer organizations—in order to accomplish key objectives and ensure timely, affordable, and responsive delivery of products and services to fighting and support units, at home and abroad. Indeed, we understand well how the efficacy of defense acquisition is inextricably dependent on workforce quality. Hence, leadership interventions along these lines appear to be highly appropriate and on target.

Assessing the impact of interventions such as these is a challenge, however (Assistant Secretary of the Navy for Research, Development, and Acquisition [ASN(RDA)], 2011a, 2011b). It is unclear whether the relatively recent BBPI, for instance, has had sufficient time to produce measurable impact. Even after two decades of the DAWIA, as another instance, efficacy remains challenging to assess, for many extant measures (e.g., number of Defense Acquisition University graduates, procurement lead times, program cost growth) fail to account for critical aspects of the AWF and important impacts on acquisition performance. Indeed, it is difficult to gauge—much less predict—the impact of any leadership interventions along these lines (e.g., how much better the AWF has become, or even if it is improving over time). Hence, the impact of any particular leadership intervention is left largely to anecdote and optimism. To help trim acquisition budgets and guide leadership, an improvement in assessing leadership initiatives and interventions is needed.

Because acquisition is a knowledge-intensive endeavor (Snider & Nissen, 2003), the knowledge stocks of people comprising the AWF represent likely indicators of quality (e.g., education levels, training courses, years of experience, certification levels). However, such indicators are relatively static, pertaining to levels of knowledge that change comparatively slowly (Nissen, 2006a). In contrast, acquisition laws, rules, and regulations are revised frequently, and acquisition knowledge can change abruptly and render obsolete even huge stocks over time. Indeed, this dynamic acquisition environment requires members of the AWF to sustain career-long learning and knowledge development just to remain proficient as acquisition professionals. Thus, as indicators of AWF quality, static knowledge stocks appear to be out of phase with the highly dynamic nature of the acquisition environment.

Moreover, acquisition organizations experience persistent flux (Snider & Nissen, 2003). We understand well that no two acquisition projects, programs, organizations, customers, or requirements are completely alike. Hence, even well-educated and well-trained people, with appropriate certification levels and years or decades of acquisition experience, must continually learn afresh and expand their knowledge further with each new assignment. Likewise, it is clear that most acquisition organizations form and reform with new people (e.g., via personnel transfer, turnover, retirement, promotion) continuously and that end customer needs shift perennially (especially at the tactical edges of warfare organizations). Due to such discontinuous membership (Ibrahim & Nissen, 2007), even these educated, trained, certified, and experienced people must learn repeatedly to trust and work effectively with many others—each time someone new joins or leaves a particular

acquisition organization, and each time a novel product, service, or customer is involved. Thus, dynamic knowledge also appears to be an important AWF quality indicator.

Further, the pace of change in both information technologies and military operations causes this importance of dynamic knowledge to apply in particular where information systems (IS) are acquired to support people at the tactical edges of warfare organizations. Not only must acquisition personnel be competent in their professions—including the acquisition and maintenance of new acquisition knowledge and skills—and continually learn afresh amidst constant organizational flux, but they must also keep pace with incessant technological change and satisfy customers' dynamic needs. Even highly competent professionals executing internal acquisition processes perfectly can fail to satisfy end customers' materiel or service needs. This presents a huge challenge in terms of assessing AWF quality.

Building on the development and application of Knowledge Flow Theory (KFT) over the past couple of decades (see Nissen, 2006b), we have developed a state-of-the-art approach that enables us to analyze, visualize, and measure dynamic knowledge and performance. This measurement-based approach offers potential to overcome the limitations of static measures, as previously summarized, by focusing inwardly on the dynamics of knowledge important to professional and effective acquisition performance. The main idea is to measure the dynamic knowledge and performance of acquisition processes (e.g., within contracting and project management organizations). This would represent a substantial step forward in terms of acquisition research.

Further, leveraging complementary research in command and control (C2; Nissen & Gallup, 2012), we see potential to use this same measurement-based approach to also look outwardly at the dynamics of knowledge important to professional and effective warfare performance. Although the specific kinds of knowledge required for effective warfare will clearly differ from those essential for proficient acquisition, the approach is similar. The main idea is to measure the dynamic knowledge and performance of warfare processes (e.g., at the tactical edges of military combat organizations). This would represent a substantial step forward in terms of C2 research.

Moreover, we seek to link these inward and outward focusing approaches to conceptualize an operational proxy for AWF quality: *end customer performance*. In addition to measuring the dynamic knowledge and performance of key people and organizations associated with IS acquisition, for instance, we wish to assess AWF quality by also measuring the dynamic knowledge and performance of primary beneficiaries of such systems acquisition: end customers operating at the tactical edges of warfare organizations. This proxy offers its best potential to complement, not replace, other metrics in conceptualization, development, and use today, but it arguably concentrates on one of the most important AWF quality determinants: how acquired systems affect operational performance. Two fundamental research questions follow accordingly:

1. How can dynamic knowledge and performance metrics be applied to assess acquisition workforce quality?
2. How can dynamic knowledge and performance metrics be extended to the tactical edges of warfare organizations?

Building heavily on the exploratory study reported by Nissen (2012b), we summarize fast-changing IS acquisition from the perspective of warfare at the tactical edge, and we discuss dynamic knowledge and performance measures to both complement and contrast with extant, engineering-oriented metrics used to specify and assess most acquired systems

today. We begin with a summary of KFT and measurement and then follow with the research method guiding the study. Results follow and suggest considerable promise, particularly where acquisition personnel and organizations can learn and track how changing system characteristics correspond with operational performance at the tactical edges of warfare organizations over time.

Background

The dynamic nature of knowledge indicates that both stocks and flows are important (Dierickx & Cool, 1989). Knowledge stocks have been comparatively straightforward to measure historically; metrics pertaining to education levels, training courses, years of experience, certifications, and like knowledge-oriented factors are employed broadly. Alternatively, knowledge flows have been comparatively much more difficult to assess; metrics pertaining to dynamic knowledge—particularly at the group and organization levels—are more elusive. The development and application of KFT (see Nissen, 2006b) over the past couple of decades has augmented the set of tools and techniques available to analyze, visualize, and measure dynamic knowledge and performance in the organization.

KFT is founded on a set of 30 principles that characterize dynamic knowledge. Such principles are actionable and empirical, and they support the diagnosis of workflow and knowledge-flow process pathologies, visualization of improvement interventions, and measurement of dynamic knowledge and performance gains (Nissen, 2006a). Dynamic knowledge is delineated via five-dimensional (5D) vector space. Knowledge-flow vectors carry measurements and elucidate diagnostic inferences pertaining to the people, processes, and organizations associated with knowledge work. Figure 1 illustrates the idea.

Briefly, the vertical axis, “Explicitness,” characterizes the nature of knowledge along a tacit-explicit continuum. Tacit knowledge implies understanding and know-how/why, and it is associated most closely with the experiences of people (e.g., stemming from job assignments, mentoring, and teamwork) and routines of organizations (including culture, process, and ritual). Explicit knowledge implies awareness and know-who/what/where/when, and it is associated most closely with artifacts (e.g., documents, formulae, software). Generally, the more tacit the knowledge, the greater its appropriability and potential impact on positive performance becomes (Saviotti, 1998). One can measure knowledge explicitness using ordinal, interval, or ratio scales.

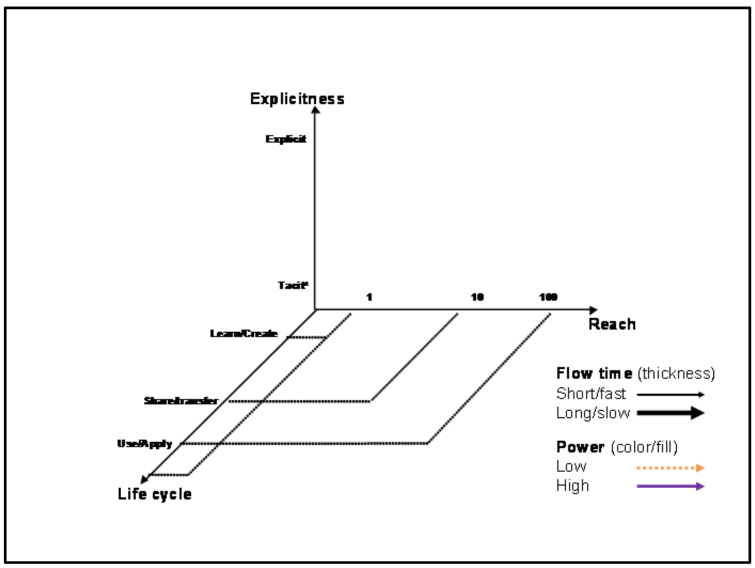

Figure 1. 5D Knowledge Flow Diagram

The horizontal axis, “Reach,” characterizes how broadly knowledge is known and shared in an organization. Here we operationalize reach in terms of the number of people in an organization who have access to and can employ any particular chunk of knowledge, but we could view reach in terms of organizational levels instead (e.g., individual, group, organization, interorganization). Generally, the broader the reach of knowledge, the greater its amplification and potential impact on positive performance becomes (Nonaka, 1994). Measurements can be made using ordinal, interval, or ratio scales.

The axis “Life cycle” characterizes what is being done with a particular chunk of knowledge at some specific point in time. Here we include three activities: (1) some individual in the organization learns or creates new knowledge; (2) he or she shares existing knowledge with or transfers it to other people in the organization; and (3) one or more people in the organization use or apply existing knowledge to accomplish work. Generally, knowledge does not become useful until it is used or applied (Pfeffer & Sutton, 1999). Measurements can be made using categorical or ordinal scales.

Because visualization beyond three dimensions is difficult, we represent the dimension “Flow time” in terms of the thickness of lines used to delineate vectors. As shown in the key to the right of Figure 1, relatively thin lines are used to delineate short and fast knowledge flows, whereas comparatively thick lines represent knowledge that takes a long time and flows slowly. Generally, the more quickly that knowledge flows (e.g., across people, organizations, places, times), the greater its potential impact on positive performance becomes (Nissen, 2002). Measurements can be made using ordinal, interval, or ratio scales.

The dimension “Power” is represented similarly in terms of line style used to delineate knowledge-flow vectors. Knowledge that flows with relatively low power—this corresponds with relatively low performance levels of organizational activities enabled by the knowledge—is delineated through orange, dotted lines, whereas knowledge flows exhibiting high power—and hence enabling high performance—are delineated via purple, solid lines. Measurements can be made using ordinal, interval, or ratio scales.

Integrating these five dimensions graphically and analytically generates a 5D vector space to examine dynamic knowledge. Such 5D space and examination schemes are completely general: they can be applied to any dynamic knowledge in any organizational domain (e.g., acquisition, C2, software engineering).

As an example of use and application, consider Figure 2, which illustrates an important knowledge flow desired by the organization. Point A represents one individual in the organization who learns something new (to that organization) or creates entirely new knowledge. In terms of the 5D space, this represents tacit knowledge that is created by an individual (i.e., one person); hence, its position at the bottom-back corner of the diagram.

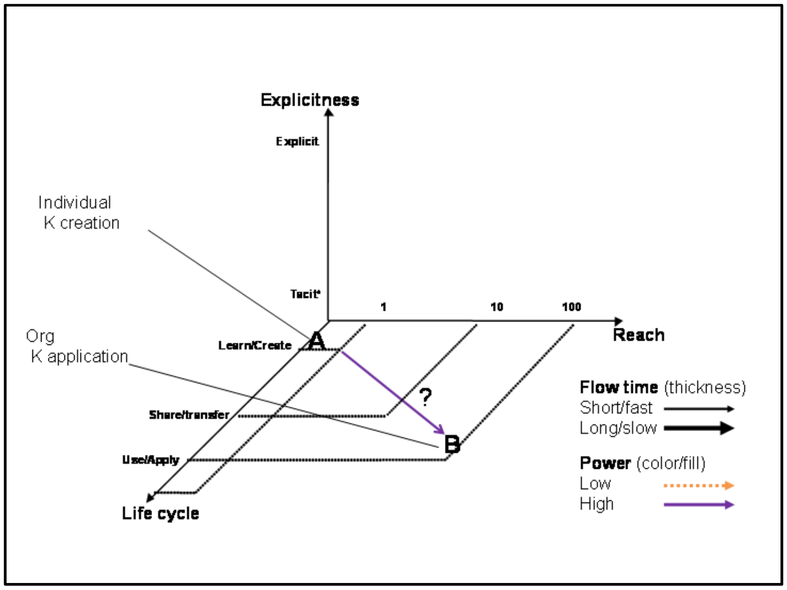

Figure 2. Knowledge Creation and Application Needs

In the acquisition domain, for instance, consider that such new knowledge could pertain to a technique for reducing the acquisition time for an important IS needed in the field. Because information technology (IT) advances so quickly—outpacing the ability of many acquisition organizations to develop and field systems responsively—the organization views this new knowledge created at Point A as important, and it would like to see such knowledge shared with and applied by all 100 people in that organization who work with IT.

Such application by 100 people in the organization is represented by Point B. The thin, purple, solid vector connecting Points A and B represents the desired knowledge flow: the organization wishes for such knowledge to flow quickly and with high power (e.g., enabling all 100 people at Point B to work, within one day, at the same performance level as the innovative individual at Point A). This represents a 5D knowledge flow vector. A question mark in the figure next to the vector indicates that such a fast, powerful knowledge flow is desired by the organization, but it is unclear which, if any, organizational process can enable it.

This leads to Figure 3, which depicts a ridge, or obstruction, that prevents knowledge from flowing quickly and powerfully from Points A to B as desired by the organization. Practically, the organization lacks a process for such quick and powerful knowledge to flow directly as delineated in Figure 2. Indeed, most organizations do lack such a process (Nissen, 2006a). Some other approach to sharing and applying the important IT acquisition knowledge is required.

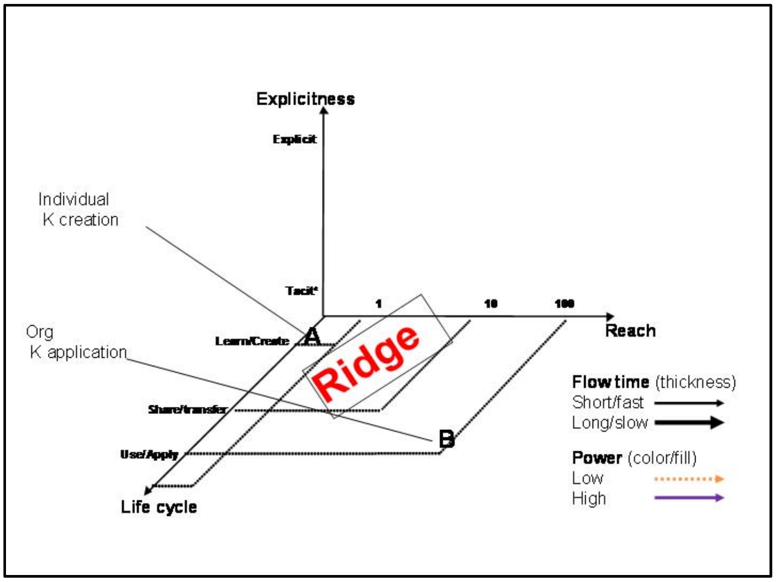

Figure 3. Knowledge Flow Obstruction

Figure 4 delineates two alternate, archetypical knowledge flows corresponding to processes that are within this organization's capabilities. (We say *archetypical* because most organizations employ these classic processes routinely, and because they present a vivid contrast in terms of how dynamic knowledge flows.) One knowledge flow is depicted in terms of a relatively fast (i.e., thin lines) but low-power (i.e., orange, dotted lines) vector series; this first flow is associated with explicit knowledge and utilizes one or more IS for knowledge articulation and distribution in explicit form. The other is delineated via a comparatively slow (i.e., thick lines) but high-power (i.e., purple, solid lines) vector; this second flow is associated with tacit knowledge and utilizes one or more human-centered approaches to knowledge sharing (e.g., group interaction, mentoring, personnel transfer).

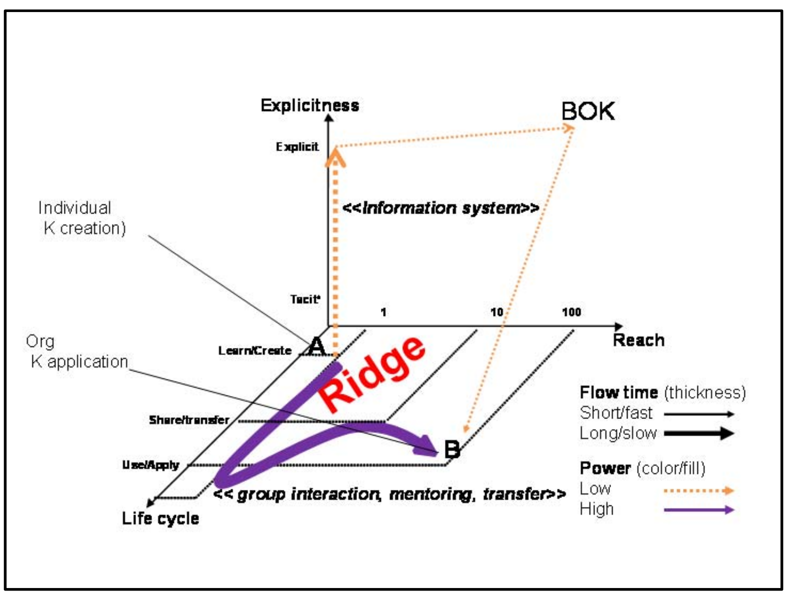

Figure 4. Alternate Archetypical Knowledge Flows

In some greater detail, the first knowledge flow consists of three vectors. The first vector is represented by a vertical line arising from Point A. This vector depicts the individual

at Point A articulating his or her new, tacit knowledge via an IS so that it can be shared electronically. Such articulation (e.g., consider writing a procedure, developing a training course, posting to an intranet or social networking site) tends to be somewhat time-consuming, hence the relatively thick line. Articulating knowledge in explicit form also tends to dilute the knowledge in terms of power. Reading a book, for instance, about how to accomplish important acquisition tasks (e.g., contract negotiation, risk assessment, balancing program cost and schedule with performance) is not the same as having direct personal experience accomplishing those tasks, hence the orange, dotted line.

Once articulated in explicit form, however—particularly via IS—the knowledge can be shared very broadly (e.g., organization-wide) and very quickly (e.g., within seconds), albeit with diluted power, hence the thin, orange, dotted line at the top of the diagram. Indeed, one could consider this broad and fast flow as additive to the organization's express acquisition body of knowledge (BOK), which we note at the top-right of Figure 4. Such an explicit BOK can then be accessed quickly and applied in turn by all 100 people in the organization. This articulated, explicit knowledge remains relatively diluted and less powerful, nonetheless, so application at Point B would not support the same performance level as at Point A, hence the thin, orange, dotted line descending down to Point B.

Alternatively, the second knowledge flow consists of a single vector, although it curves and bends through the tacit knowledge plane at the bottom of Figure 4. This vector depicts the individual at Point A applying his or her new, tacit knowledge and then sharing it with some number of other people (say, 10 people, as illustrated in Figure 4) through one or more techniques, such as extended group interaction, mentoring, or personnel transfer to work directly with different coworkers across the organization.

Once each of these 10 people has learned the new, tacit knowledge, then all of them can continue the process and share it using similar techniques (e.g., group interaction, mentoring, or personnel transfer) with others. Through such a process, 100 people (i.e., 10 people each sharing with another 10 people) can learn this new, tacit knowledge to the extent necessary for powerful application at Point B. This knowledge flow is depicted by a thick vector to indicate that it occurs comparatively slowly, but such vector is also delineated by a purple, solid line to show that the corresponding knowledge has high power and enables knowledge-based action at the same performance level as the individual who created it at Point A.

The key is that one can measure these five dimensions of knowledge—whether via explicit or tacit flows—and relate them to the corresponding knowledge-based process performance by people in the organization. Indeed, by correlating such dynamic knowledge measures with performance metrics, one can develop a model capable of analyzing, visualizing, and even predicting process performance based on knowledge flow patterns.

Of course, many diverse combinations of these archetypical knowledge flows are possible too, yet most knowledge flows are likely to reflect some aspects of these two dynamic patterns (Nissen, 2006b). Through empirical analysis and calibration of specific knowledge flowing through any particular organization in the field, one can correlate 5D dynamic knowledge flows with work performance, resulting in a model capable of measurement and prediction. Through this technique, we are working to assess AWF quality in terms of dynamic knowledge flows.

Research Method

The first research question, articulated previously, includes a "how" interrogative and suggests that a qualitative method may be most appropriate to investigate it (Yin, 1994). Despite the generality of KFT and the 5D space described in the previous section, applying

the corresponding analytic, visualization, and measurement techniques to assess AWF quality requires acquisition domain knowledge in general and process-specific understanding in particular. We need to study one or more specific acquisition processes in detail in order to apply the techniques and assess workforce quality. The case study method is highly appropriate for an investigation along these lines (Benbasat, Goldstein, & Mead, 1987; Eisenhardt & Graebner, 2007; Yin, 1994), and we conduct just such a case study in parallel with the investigation reported here.

The second research question, stated previously, also involves a “how” interrogative, and it likewise suggests a qualitative method. However, this second question calls for an extension of dynamic knowledge and performance measurement out to the tactical edges of warfare organizations and hence is much more exploratory from an acquisition perspective. Because we seek an operational proxy for AWF quality, we investigate dynamic knowledge and performance through explicit examination of three warfare organizations and processes that are far removed from core acquisition.

One organization operates within a U.S. Navy fleet and has units deploying rhythmically to war zones and other areas overseas. A second organization operates within a Navy systems command but concentrates on ensuring the readiness of this same fleet. The third organization permeates functionally throughout naval operations and is responsible for information dominance. By interacting with knowledgeable representatives from each of these three organizations—and it is very important to note that these are warriors and other operational personnel, not acquisition professionals—we gain considerable insight into the key knowledge dynamics associated with warfare at the tactical edges.

Further, by triangulating between these three organizations, we identify a critical, knowledge-intensive process that can be represented with sufficient fidelity and granularity to suggest feasible application of our dynamic knowledge and performance measures. The process has the somewhat unwieldy name *Tasking, Collection, Processing, Exploitation, and Dissemination*, to which we refer simply by its acronym TCPED. In the results that follow, we delineate the TCPED process and seek to apply our dynamic knowledge and performance measures to it. We then attempt to interpret such application and to elucidate insight into assessing AWF quality via proxy.

Results

Results from this exploratory investigation center on delineating the TCPED process, elaborating an insightful subprocess in detail, and applying our dynamic knowledge and performance measures to it. We discuss these in turn and then focus on elucidating insight into AWF quality.

TCPED

TCPED does not represent a new operational process per se, but with the U.S. Navy’s relatively recent creation of its Information Dominance Corps, it has attracted considerable attention as a critical complement to the find, fix, target, and track (F2T2) process associated broadly with combat operations. The key F2T2 issue remains “knowledge—finding the targets” (Keeter, 2004), and as a knowledge-intensive process, TCPED addresses this issue directly, and hence represents a promising target of study.

Given the knowledge-intensive nature of TCPED, its execution is enabled fundamentally by IT, and IS are acquired routinely with the goal of enhancing warfare efficacy. This nature provides an excellent link back to our fundamental research question and interest in the AWF. From the operational perspective of TCPED participants at the

tactical edges of organizations, IS acquired and fielded to enhance warfare efficacy should accomplish just that: enhance warfare efficacy. Further, such efficacy enhancement should be measurable.

The problem is, it is difficult to understand—much less measure—how well any particular warfare process is working, which of many different organizational arrangements are best across diverse missions, or how well various IS enhance or impede the process. Indeed, when seeking to acquire new IT and like technologies to enhance warfare efficacy, system implementation can make the operational processes worse in the battle space, and it is increasingly common for different acquired systems to fail in terms of interoperating (Nissen & Gallup, 2012).

Indeed, modern warfare efficacy requires a combination of people and technologies to enable warriors to leverage local knowledge and seize emergent opportunities to achieve commanders' intent across distributed organizations. This requirement highlights further the critical role played by TCPED, which seeks to enable commanders and warriors at the tactical edges to put dynamic knowledge into effective action, with or without IS in development or in the field.

Additionally, unlike many stable, mature, and well-understood warfare processes, TCPED remains in a constant state of analysis, refinement, and development. Hence, it represents a rapidly moving target for IT development, and engineering-oriented metrics used to evaluate most IS fail to address how dynamic knowledge translates into effective (or ineffective) action. Moreover, with current analytical models and metrics, it remains unclear how to assess whether any particular refinement in the warfare process, new IS implementation, or like change will lead to increased TCPED efficacy or whether performance will degrade instead. This lack of clarity illuminates a capacious gap between the efficiency of IT acquisition and the warfare efficacy of IS employment at the tactical edge.

Given the dynamic nature of the TCPED process, as characterized previously, we bound the scope of this exploratory project by concentrating on a particularly important and knowledge-centric subprocess: *exploitation*. Such bounding enables us to examine, within a single exploratory study, the feasibility of our approach to measuring the dynamic knowledge and performance of this operational process performed at the tactical edges of naval organizations. Follow-on researchers can then extend these promising results via subsequent studies through the process as a whole and, in turn, to other warfare processes seeking to benefit from IT acquisition.

TCPED Exploitation

Figure 5 delineates the principal tasks comprising TCPED exploitation. In this figure, process activities are depicted as rectangular boxes connected to one another via arrows to delineate the process workflow. Each process activity is situated within a horizontal region (referred to widely as *swim lanes*) that depicts the responsibility of a particular organizational group to accomplish it. For several instances, the leftmost process activities—"Correlate, Fuse Multi-Int Info" → "Operations Environment Impact" → "Evaluate Adversary" → "Develop Adversary COA"—are shown connected together as responsibilities of the "Assessor" group; the "Develop Adversary COA" activity interrelates with "Watch Analyst Coordination," the latter of which is shown as the responsibility of the Joint Intelligence Operations Center (JIOC), and which interrelates in turn with the Joint Operations Center (JOC) activity "Watch Coordination."

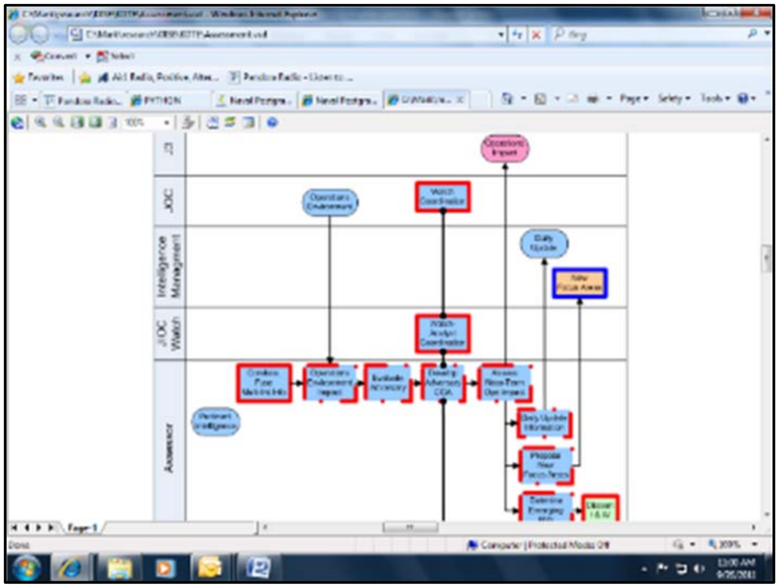

Figure 5. TCPED Exploitation Process Flow

Other instances pertain to “Assess Near-Term Ops Impact,” the output of which activity provides important knowledge and information to Operations (“J3”); “Daily Update Information” and “Propose New Focus Areas,” the output of which activities provide important knowledge and information to intelligence management; and “Determine Emerging I&W” and “Dissem I&W,” both of which activities are performed by and are the responsibility of the assessor as well. We omit graphical depiction or discussion of the other TCPED exploitation activities because our intent is not to be exhaustive here, and these should suffice for our present purposes.

In particular, discussions with the knowledgeable people interviewed through this research indicate that the tasks labeled “Evaluate Adversary,” “Develop Adversary COA,” and “Assess Near-Term Ops Impact” are especially important and require considerable tacit knowledge. Recall that tacit knowledge, as powerful as it is, tends to flow relatively slowly and narrowly through organizations. This makes it particularly challenging to support via IT, and it provides an excellent focus for our exploration. Indeed, the people performing these activities must develop substantial, tacit knowledge pertaining to adversaries’ capabilities, likely actions, and their consequences in terms of friendly forces and operations. Such tasks also clearly require relevant and timely information, but knowledge of the adversary is key here, and the effectiveness of these tasks can contribute greatly to—or, if ineffective, impair instead—commanders’ decision-making and warriors’ actions on the tactical edge.

By focusing on how dynamic knowledge flows through warfare process activities such as these, and especially by linking the activities to knowledge-based actions enabled at the tactical edge, we can examine how well knowledge is flowing and supporting tactical action. Specifically, by integrating the organizations, personnel, and activities included in the exploitation process diagrammed in Figure 5 with key dimensions from KFT, we seek to identify critical paths in the process where knowledge is flowing well and appropriately, as well as identifying blocked paths where it is not, and we strive to use our dynamic knowledge and performance metrics to help overcome any disconnects between IT acquisition and warfare efficacy.

Dynamic Knowledge Flows

Through detailed analysis, we can delineate the principal knowledge flows enabling TCPED exploitation. Taking Develop Adversary COA as an express example, the people performing this activity rely fundamentally on experience-based tacit knowledge (e.g., military tactics, adversary capabilities, organizational vulnerabilities). Although formal training courses, professional educational programs, and like approaches contribute to these knowledge flows, such knowledge is accumulated principally through direct experience (i.e., on-the-job training [OJT]), often over many years or even decades.

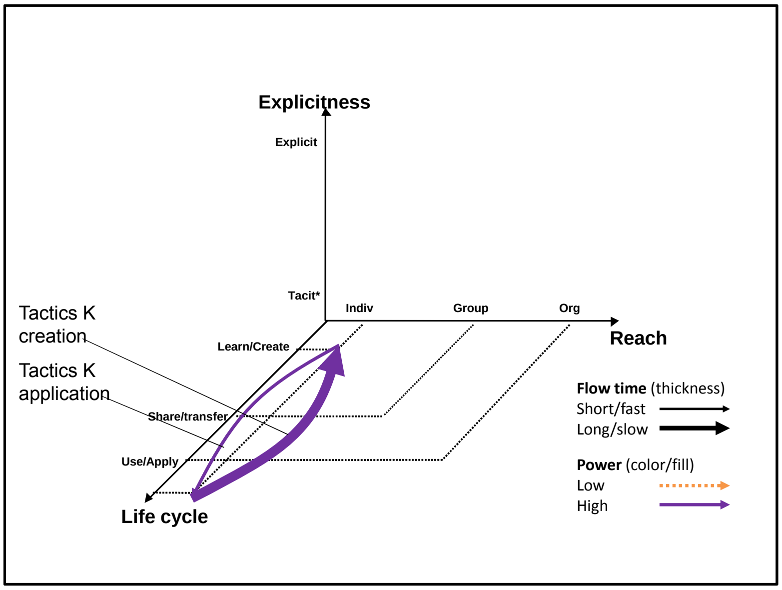

Figure 6. Military Tactics Knowledge Flows

Figure 6 delineates how military tactics knowledge, for instance, accumulates through cyclic iteration between applying one's existing tacit knowledge (labeled "Tactics K application" in the figure) and learning from the resulting experience (labeled "Tactics K creation" in the figure). We locate this cyclic knowledge flow vector at the individual level of reach, indicating that the Develop Adversary COA activity is conducted in this case by a single individual. Were multiple people to engage jointly in assessments such as this, we would simply relocate the corresponding knowledge flows to the group level, with the same basic pattern persisting.

Consistent with our previous discussion, one can observe from Figure 6 how the vector for knowledge application is relatively thin, denoting that the flow is correspondingly fast; yet this vector is delineated via a purple, solid arrow, denoting that the flow reflects powerful, tacit knowledge. That is, once tacit knowledge has been acquired over time, it can be applied relatively quickly. In partial contrast, the complementary vector for knowledge creation is comparably thick, denoting that the knowledge acquisition flow is relatively slow; yet this vector is also delineated via a purple, solid arrow, similarly denoting that the flow reflects powerful, tacit knowledge.

Continuing with the Develop Adversary COA example, the people performing this activity also rely on a situated understanding of the organization's current mission-environment context, the adversary evaluation synthesized in the preceding exploitation process step, and contemporaneous knowledge regarding both current and future operations being conducted and planned, respectively, by the organization. Knowledge flowing to enable these process activities follows somewhat different patterns than those

activities pertaining to military tactics. In particular, these latter knowledge flows involve interactions across different organizational groups, and they involve both tacit and explicit knowledge.

For instance, Figure 7 delineates three knowledge flows associated with tacit knowledge sharing and intergroup accumulation. The leftmost cyclic vector (labeled "Individual K accumulation") is comparable to that discussed previously in Figure 6, except that instead of military tactics knowledge, it pertains to the latter knowledge flows (e.g., associated with current mission-environment, adversary evaluation, and current and future operations). We continue to focus on individual knowledge accumulated by a single person—in this case, within the assessor group—but notice that we include a similar cyclic vector located at the intergroup level.

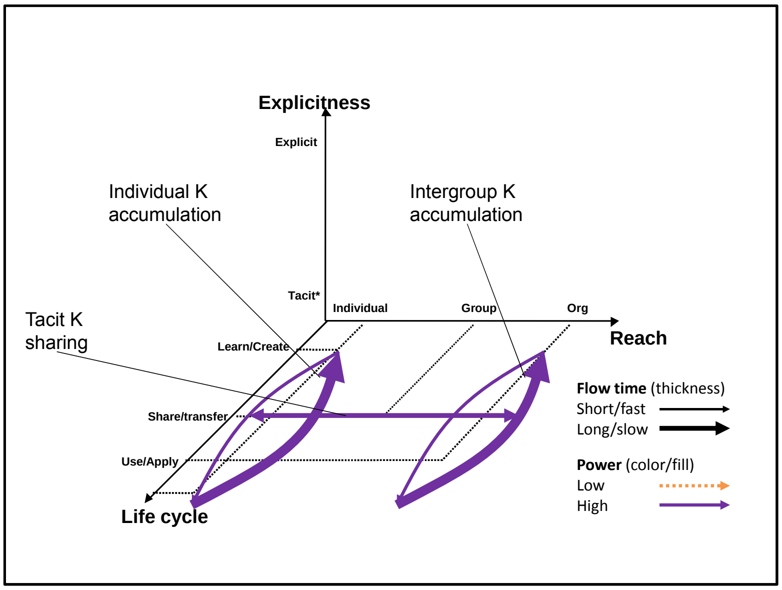

Figure 7. Tacit Knowledge Sharing and Intergroup Accumulation

This latter vector (labeled "Intergroup K accumulation") reflects tacit knowledge accumulating across different organizational groups; multiple individuals from a variety of groups work and learn from their experiences together. The intergroup vector follows the same cyclic pattern as that seen with individual OJT, only at a higher organizational level. As with individual knowledge accumulation, this intergroup accumulation is delineated by a cyclic, purple, solid vector reflecting knowledge application and creation occurring at two different rates: quickly and slowly, respectively.

A third vector (labeled "Tacit K sharing") links the other two. Such tacit knowledge sharing reflects individuals—who accumulate knowledge (especially via OJT) within their separate groups—sharing knowledge with people in other groups through conversation, dialogue, face-to-face (F2F) interaction, and like means. The two-headed arrow included with this sharing vector depicts knowledge flowing bi-directionally: individuals share knowledge across groups in the organization, and they also learn through this knowledge process.

As with the two cyclic vectors delineated and discussed previously, knowledge flows corresponding to such tacit sharing are depicted with a purple, solid vector to designate powerful tacit knowledge, and the vector is depicted with a relatively thick line to indicate that tacit knowledge flows across organizational groups tend to accumulate relatively slowly. However, we depict this sharing vector with a line that exhibits intermediate thickness; that

is, the vector is thicker than the application vector lines—suggesting that tacit knowledge application flows across groups (e.g., in a matter of days, weeks, and months) more slowly than via individual application (e.g., in a matter of minutes, hours, and days)—but thinner than the creation vectors—suggesting that such cross-group knowledge can flow more quickly than can individual accumulation of experience-based tacit knowledge (e.g., in a matter of months, years, and decades).

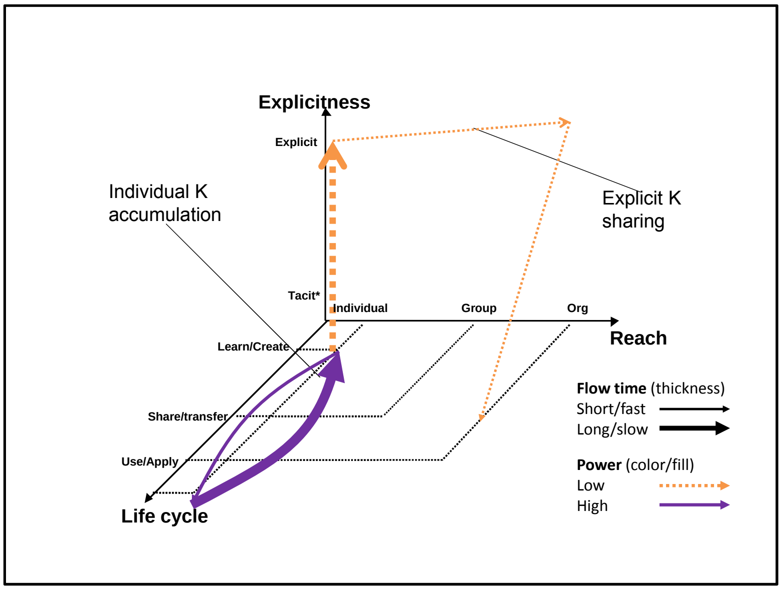

Figure 8. Explicit Organizational Knowledge Sharing

As another instance, Figure 8 delineates alternate knowledge flows associated with explicit organizational knowledge sharing. The leftmost cyclic vector (labeled "Individual K accumulation") is identical to that discussed previously in Figure 7 (e.g., cyclic, purple, solid, powerful, tacit). We continue to focus on individual knowledge accumulated by a single person—in this case, within the assessor group—but notice that we include a three-segment flow (labeled "Explicit K sharing") to depict knowledge being shared organization-wide in explicit form.

This three-segment flow begins with a vertical vector rising up out of the tacit plane, as an individual (i.e., in the assessor group) articulates his or her tacit knowledge into explicit form (e.g., via textual reports, graphical sketches, digital images). This articulation can be a time-consuming process; hence, the corresponding knowledge flow vector is depicted by a relatively thick line. In addition, we understand that such articulated, explicit knowledge does not reflect the same power level as the tacit knowledge used for its creation; hence, the corresponding knowledge flow vector is depicted by an orange, dotted line.

The second vector comprising this three segment flow begins where the first vector terminates. Once articulated in explicit form, such knowledge can be stored, replicated, and disseminated quickly and broadly via one or more IS (e.g., intranet document repositories, online sharing tools, common operational displays). This second vector in the segment is delineated by a thin line to denote fast knowledge flows, but the line remains orange and dotted to depict its diluted power. The third vector in the segment is also depicted by a thin, orange, dotted vector, which represents this same, diluted, explicit knowledge flowing via IS quickly and broadly across the organization.

Dynamic Knowledge and Performance Measurement

Through detailed analysis, we identify and operationalize three KFT metrics that appear to be particularly insightful for our present purposes: *knowledge reach* (i.e., how many people in the organization share specific chunks of knowledge), *knowledge flow time* (i.e., how long it takes chunks of tacit and explicit knowledge to flow from where and when they are to where and when they are needed), and *knowledge power* (i.e., the performance level of knowledge-enabled work). Continuing with Develop Adversary COA as an express example, we can begin to quantify the key knowledge flows delineated previously.

Table 1. ROOM Knowledge Flow Measurement

Knowledge Flow	Reach	Flow Time	Power
Individual K Accumulation	1	Years	Very High
Intergroup K Accumulation	10	Months	High
Tacit K Sharing	10	Days	High
Explicit K Sharing	100	Hours	Diluted

For instance, Table 1 summarizes rough order of magnitude (ROOM), 3D estimates for each of the four knowledge flows delineated and discussed previously with respect to the Develop Adversary COA activity within TCPED exploitation. In this table, we approximate knowledge flow measurements only to an order of magnitude, but we begin to illustrate the use and utility of the approach, and we outline a method for obtaining higher fidelity measurements in practice.

In the first column of the table, we list each of the four knowledge flows discussed previously; and in the other three columns, we summarize ROOM estimates for knowledge reach, flow time, and power. Looking first at individual knowledge accumulation, the reach is listed as 1; this reflects our previous discussion of knowledge being accumulated iteratively at the individual level, hence unitary reach. In the table, flow time is listed in order of magnitude as “years” for comparison with the other knowledge flows; this reflects our discussion about how deep, experience-based tacit knowledge (e.g., pertaining to military tactics) can require years or decades to accumulate. Power is listed likewise in order of magnitude as “very high” for similar comparison with the other knowledge flows; this estimate is somewhat definitional, but it reflects that experience-based tacit knowledge does not suffer from power dilution, and it is meant to reflect the considerable power of tacit knowledge accumulated over long periods of time and through abundant experience.

Looking next at intergroup knowledge accumulation, rough estimates for this knowledge flow indicate that 10 people can be reached by it; this is an order of magnitude larger than that shown for individual knowledge accumulation, and it reflects knowledge flowing to multiple people across organizational groups. The flow time estimated for intergroup knowledge flows is summarized as “months,” which is an order of magnitude faster than that for individual knowledge accumulation; this reflects the comparatively lower level of deep knowledge associated with intergroup knowledge and work flows, as people across groups interact principally via their present assignments—which, in this naval context, generally span less than a year. As discussed previously, the power level is listed simply as “high” to reflect that intergroup tacit knowledge (e.g., people learning to work well together across groups) does not suffer from power dilution, but it also reflects that the power level is not comparable to that associated with deep, experience-based knowledge accumulated over years of individual experience (e.g., pertaining to military tactics).

Estimates for the third knowledge flow (i.e., tacit knowledge sharing) are similar in terms of reach (10), but they reflect more than another order of magnitude reduction in flow time (i.e., "days"); this corresponds to the principle that knowledge sharing can be accomplished more quickly than the associated knowledge accumulation (Nissen, 2006b). The ("high") power level matches that for intergroup accumulation mentioned previously and for the same reasons.

In considerable contrast, the flows associated with the fourth knowledge flow (i.e., explicit knowledge sharing) are quantitatively very different. We estimate the reach at 100 in the table, but the knowledge flows are constrained only by the reach of the network infrastructure; hence, this figure could be many orders of magnitude larger (e.g., consider a report, through which everyone in a 100,000 person organization has access to the same explicit knowledge). The estimate for flow time is similar in that we list it as "hours" (e.g., principally to account for the time required to articulate knowledge in explicit form), whereas once made explicit, such knowledge can be shared in seconds.

Moreover, the power level ("diluted") for this explicit knowledge flow is qualitatively different from that for its tacit counterparts; this is also somewhat definitional, but it indicates that most people reading written documents, for example, will not be expected to perform knowledge-based activities at the same level as the people writing those documents.

System Assessment

The remaining measurement of knowledge power is linked directly to performance of the work activities enabled by such knowledge. In the case of Develop Adversary COA, to continue our previous example, we could approach such measurement via multiple operationalizations. For several instances, we could track how much time is required to develop a set of adversary COAs sufficiently well for inclusion in a morning flag brief (i.e., appropriate for presentation to a flag officer); using the same flag brief criterion, we could count how many sufficiently credible adversary COAs are developed within a set time frame (e.g., one day, week, or month); we could ask the flag officer and staff in question (including the Chief of Staff and other directly reporting officers) to evaluate the quality of each adversary COA presented (based on criteria of importance to them); or we could pursue the development of other, likewise understandable and relevant performance measures. Any such performance measure can serve as a quantitative (and possibly multidimensional) proxy for knowledge power.

With one or more such measures in hand, we could then establish a baseline—comprised of quantitative measurements for *reach, flow time,* and *knowledge power/performance*—for the organization as it operates as usual. To evaluate some particular IS, we could simply compare this baseline with measurements taken as the organization uses the IS under controlled, or at least comparable, conditions. For instance, say that we wish to test a prototype IS designed to improve tacit knowledge sharing through introduction of social media techniques; we could measure the knowledge flows both with and without such IS to assess its impacts.

Specifically, using one or more proxy measures as suggested previously (e.g*., time required to develop a set of adversary COAs for a flag brief, how many adversary COAs are developed, flag officer quality evaluation,* others), we could conduct an experiment in the laboratory or in the "field" (e.g., on deployed ships at sea) and measure knowledge and performance directly. As an experiment to compare performance with and without the prototype IS, for instance, we would ideally like to see the same people, performing the same tasks, in the same environments and settings, at the same times of day, seasons of year, weather conditions, sea states, and other factors to isolate use of that IS as the only

difference. In other words, one set of dynamic knowledge measurements would be taken for performance in the baseline situation; a second set of measurements would be taken for performance with a prototype IS; and, ideally (e.g., with good experiment design and techniques), the difference would represent solely the effect of that IS.

With these measurements in hand, the difference in task performance becomes an operational measure of IS efficacy; that is, if the only difference between experiment cases is whether the prototype IS used or not, and task performance is measurably better or worse in one case or the other, then we have a knowledge-based assessment of how well such IS improves (or worsens) work performance at the tactical edge of the organization (e.g., TCPED exploitation). Moreover, in addition to using traditional, engineering-oriented performance measures (e.g., bandwidth, technical reliability, memory), this assessment can be employed to evaluate the IS operationally—and under controlled conditions—not just technically. The potential is huge.

Further, given sufficient experience with conducting experiments along these lines, this approach can even be used to specify new IT and other systems to be acquired; that is, in conjunction with using only engineering measures of IS performance, for instance, the acquisition organization can specify *improvement in operational task performance* as a key criterion for evaluation. This way, acquisition personnel can conduct efficient system acquisitions, and warriors on the tactical edges of organizations can use systems that improve their work performance. We bridge the gap between acquirer and warrior, and everybody wins.

Illustrative Example

In this section, we include an illustrative example of application to a hypothetical IT system competition. We use only representative values for illustration here, but the approach and associated techniques can be applied directly to system competitions in the field. For continuity, we continue with the Develop Adversary COA task discussed previously, and we build upon the rough knowledge flows and measurements reported previously.

Table 2. Baseline Knowledge Flow Measurement

Knowledge Flow	Reach	Flow Time	Power	X-Power
Tacit K Sharing	10	20 Hours	95%	9.5
Explicit K Sharing	100	2 Hours	5%	5.0

Table 2 recapitulates the most relevant measurements reported in Table 1 for what we term the baseline, representing the Develop Adversary COA task as it is performed today (i.e., sans new IS); that is, the baseline measurements are used for comparison with this same task performed with the support of two competing IS prototypes: (1) a social media application designed to improve tacit knowledge sharing, versus (2) a document collaboration application designed to improve explicit knowledge sharing.

Notice in Table 2 that we limit our summary to the pair of knowledge flows associated directly with the alternate IS: tacit knowledge sharing (addressed by IS-1) and explicit knowledge sharing (addressed by IS-2). Recall, from our discussion above, that the knowledge flow corresponding to tacit knowledge sharing reflects individuals—who accumulate knowledge (especially via OJT) within their separate groups—sharing knowledge with people in other groups through conversation, dialogue, F2F interaction, and like means. The central idea of IS-1 is to enable such knowledge sharing remotely; that is,

the IS intends to enable and promote tacit knowledge sharing without the need for (as much) F2F interaction.

Recall, further from our discussion above, that the knowledge flow corresponding to explicit knowledge sharing reflects organizational artifacts (e.g., textual reports, graphical sketches, digital images, and like media) that are stored, replicated, and disseminated quickly and broadly via intranet document repositories, online sharing applications, common operational displays, and like tools. The central idea of IS-2 is to enable recipients of assessor reports (e.g., in the JIOC and JOC groups) to interact with assessors during report development; that is, the IS intends to enhance and accelerate explicit knowledge sharing by providing recipients with access to assessor draft reports and to enable communication before finished reports are released officially.

Notice also that we replace the ROOM estimates from Table 1 with quantitative values. For instance, the “days” flow time estimate from above for the tacit knowledge sharing flow reads as “20 hours” in Table 2. Based on observation and discussion, roughly 20 hours are required for key tacit knowledge to complete its flows. Further, the “high” power estimate from above reads as “95%” here. As such, 10 different people outside the assessor group (e.g., in the JIOC and JOC) are able to explain the details of each adversary COA from memory with 95% accuracy on average; the other way to look at this is that 19 of 20 people can explain the details with 100% accuracy.

Similarly, the “hours” flow time estimate from above for the explicit knowledge sharing flow reads as “2 hours” here. This indicates that roughly two hours are required for a high-quality and credible adversary COA to be articulated, shared with, and understood by recipients. Further, the “diluted” power estimate from above reads as 5% here. As such, 100 different people outside the assessor group (e.g., in the JIOC and JOC) are able to explain the details of each adversary COA from memory with 5% accuracy on average; the other way to look at this is that five of 100 people can explain the details with 100% accuracy.

Notice, finally, that we include a fifth column in Table 2 (labeled “X-Power”) to represent the induced dimension *extended knowledge power*. Extended knowledge power is calculated as the product of knowledge reach and power levels; it reflects the combined distribution and efficacy of knowledge flows. For instance, the extended knowledge power for the tacit knowledge sharing flow is shown in Table 2 as 9.5 (i.e., reach of 10 [times] power of .95 = x-power of 9.5), whereas the value calculated for explicit knowledge sharing flow is shown as 5.0 (i.e., reach of 100 [times] power of .05 = x-power of 5.0).

This respective induction and quantification of the extended knowledge power dimension and measure provide us with a technique for comparing the efficacy of tacit and explicit knowledge flows directly, despite the significant differences between their dynamic characteristics and behaviors (e.g., quick, broad, diluted explicit flows versus slow, narrow, powerful tacit flows). Clearly, higher values are preferred over lower ones, but organizations face trade-offs regarding whether to emphasize explicit or tacit knowledge flows.

Table 3. Information Systems Supported Knowledge Flow Measurement

Knowledge Flow	Reach	Flow Time	Power	X-Power
Tacit K Sharing (IS-1)	20	20 Hours	75%	15.0
Explicit K Sharing (IS-2)	20	2 Hours	10%	2.0

For further illustration, Table 3 summarizes these same knowledge flow measurements—for the same people, organizations, tasks, and time frames—after the

prototype IS have been implemented and trained with. This point is important; one cannot expect a new IS to be used effectively and productively before its users have been trained adequately. (It is humorous, nonetheless, how often one sees comparisons made without adequate training, particularly in field experiments.)

In the case of tacit knowledge sharing supported by IS-1, say that the social media application enables twice as many people to participate in the conversations (i.e., reach extends to 20) within the same 20-hour time frame (e.g., by obviating the need for collocation), but the power level decreases to 75% (e.g., due to losses via mobile social media applications). Despite the drop in power, the extended reach would more than make up for the loss, because of the extended power increase to 15.0. Alternatively, in the case of explicit knowledge sharing supported by IS-2, say that the document-sharing application reduces to 20 the number of people who can participate effectively within the same two-hour time frame (e.g., due to interference by multiple people interacting with the same documents), yet the power level of those who do participate increases to 10% (e.g., stemming from increased textual interaction across organizational groups). Despite the increase in power, the reduced reach would more than offset the gain because of the extended power decrease to 2.0.

Table 4. Comparative Knowledge Flow Measurement

Knowledge Flow	Baseline (X-Power)	IS Enabled (X-Power)	Difference (X-Power)	Difference (Percentage)
Tacit K Sharing	9.5	15.0	+ 5.5	+ 58%
Explicit K Sharing	5.0	2.0	- 3.0	- 60%

In Table 4, we summarize the comparative results via four measurements. First, the Baseline X-Power contrast between the tacit and explicit knowledge sharing processes reflects our result from Table 2 (i.e., 9.5 versus 5.0, respectively). Second, the IS Enabled X-Power contrast between these same processes reflects similarly our result from Table 3 (i.e., 15.0 versus 2.0, respectively). Third, the Difference X-Power contrast measures the effect of incorporating the two IS. For instance, using IS-1 to support tacit knowledge sharing increases extended knowledge power by 5.5 (i.e., 15.0 – 9.5 = +5.5) for a 58% gain. In contrast, using IS-2 to support explicit knowledge sharing decreases extended power by 3.0 (i.e., 2.0 – 5.0 = -3.0) for a 60% loss.

Recall that the knowledge power measurement relates directly to organizational performance at the tactical edge, on the Develop Adversary COA task in this illustrative case. In addition to providing an objective and quantitative approach to assessing the potential value (or harm) of an IS of interest, the technique described in this report also suggests a way to specify performance requirements for candidate IS of interest.

Consider, for instance, if—in addition to whatever engineering specifications are desirable or customary—the specification read along the lines of, "the IS must demonstrate at least a 25% increase in X-Power measured during a fleet experimentation exercise." This specification would arguably place considerable contractor emphasis on improving knowledge flow and work performance of users at the tactical edges of the warfare organizations targeted for the acquisition and implementation of their IS. It would also appear likely to help bridge the gap between acquisition efficiency and warfare efficacy.

Building on these results, one can now apply the approach described in this report to any number of IS acquisitions and use *end customer performance* as an objective measure

of IS efficacy. This application will require some venue for (at least partially controlled) experimentation (e.g., in the laboratory, via field experiments, phased or blocked implementation), but the potential benefit is huge. Moreover, in addition to using dynamic knowledge and process measurement as illustrated here for evaluation, one can leverage the same set of measures to specify IS in the conceptualization, design, and development phases. Essentially, *end customer performance* becomes an objective design consideration through this revolutionary approach.

In terms of measuring AWF quality, this research establishes stronger and more direct linkages between what acquisition personnel know (especially focused internally on acquisition organizations and processes) and what warriors on the tactical edges of organizations need (especially IS that improve warfare efficacy), and it provides a set of dynamic knowledge and performance measures that can be used to bridge the gap between acquisition efficiency and warfare efficacy. This measurement step alone offers potential to improve the effectiveness of those acquisition people and organizations that implement the approach described in this report; hence, one new measure of AWF quality emerges directly: *use of dynamic knowledge and process measures to assess end customer efficacy*. In other words, the working hypothesis is that those acquisition people and organizations that use this approach will be more effective than those that do not; hence, simply assessing the extent to which this approach is used may become an important, complementary measure of AWF quality.

Further, results from this research suggest that personnel in the AWF may benefit from increased understanding of the end customers for whom they acquire information and other systems. The acquisition system as a whole provides program offices, liaisons, needs determination and justification steps, milestone and oversight authorities, operational testing and evaluation, and myriad other steps seeking to represent end customers. Nonetheless, there may be no substitute for acquisition personnel who understand their customers in considerable detail.

These results do not suggest that procurement clerks should be outfitted with helmets, rifles, and boots and then sent to the tactical edges of warfare organizations, or that warriors on such tactical edges should be given procurement assignments; rather, it suggests that by examining the key warfare processes performed at the tactical edges—and in particular, understanding the most important dynamic knowledge and performance characteristics of such processes—even procurement clerks in offices half a world away may gain important insight into their end customers—insight that may lead to improved workforce quality and that can be measured.

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Outcome-Focused Market Intelligence: Extracting Better Value and Effectiveness From Strategic Sourcing

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Abstract

A relatively new approach to government procurement—strategic sourcing—offers substantially increased efficiency and effectiveness to those agencies that seek to implement its tenets. Sound market intelligence is the foundation of effective strategic sourcing. The government's current approach to market intelligence is ad hoc, inconsistent, and redundant because information is rarely shared between buying activities. Additionally, market research is treated as static, sought only to support pre-award acquisition decisions. This article offers a new paradigm for market research/market intelligence and demonstrates ways in which continuous market research/market intelligence will drive the government to achieve desired strategic sourcing outcomes. This article examines many facets of strategic sourcing, including goal setting, strategic cost management, and volume consolidation strategies. The

article concludes with recommendations for enhancing the collection of, dissemination of, and response to market research/intelligence.

Introduction

The federal acquisition system promulgates several objectives in acquisition: to procure goods and services in terms of cost, quality, and timeliness that meet customer needs; to fulfill public policy objectives (e.g., socio-economic); to minimize administrative costs; to ensure integrity, transparency, and fairness to the public; and to attain the best value. The state of the U.S. economy and the looming government budget constraints elevate the relative importance of efficiency as a key acquisition objective. A relatively new approach to government procurement—*strategic sourcing*—offers increased efficiency and effectiveness to those agencies seeking to implement its tenets. The GAO (2012) contended that billions of dollars can be saved annually by strategic sourcing, and criticized government agencies for their lack of commitment to and the subpar results produced by strategic sourcing.

There is a reasonable explanation for the lack of results. Strategic sourcing is not a quick, easy panacea. It requires experienced personnel with strong business acumen, a disciplined process, alignment of organizational goals and resources, leadership, awareness of the organizations' needs and the marketplace's capabilities, and a culture that rewards innovation. Hence, sound market intelligence is the foundation of effective strategic sourcing. Market intelligence can reveal whether goals (e.g., cost savings/avoidance) are attainable. Agencies' resources are limited; market intelligence can help agencies conduct opportunity assessments to discern which products and services should be strategically sourced. Additionally, market intelligence can unveil which acquisition strategies will achieve the greatest efficiencies.

Unfortunately, this area of great need is also an area of great weakness. The government's current approach to market intelligence is ad hoc, inconsistent, and redundant because information is rarely shared between buying activities. Additionally, no existing research or policy addresses how to properly organize or resource the collection and use of market intelligence. Furthermore, specific skills for determining needed information, finding it, analyzing it, and disseminating it are not systematically taught or developed in the government's acquisition workforce.

Therefore, the purpose of this article is to explore ways in which market intelligence can help the government achieve its desired strategic sourcing outcomes. It examines many facets of strategic sourcing, including goal setting, strategic cost management, and volume consolidation strategies and associated socio-economic support. At conclusion, it should be apparent that market intelligence need not be just another checklist requirement; rather, it can be a gateway to attaining significant results.

The article is organized as follows. First, historical and other background information surrounding market research/intelligence (MR/MI) is reviewed. Next, a brief review of key theoretical underpinnings is provided. A new model of MR/MI is proposed, which is then demonstrated in three strategic sourcing applications. Finally, conclusions and recommendations are offered.

Background

Market intelligence (a.k.a., market research) has been a statutory requirement since the passage of the Competition in Contracting Act (CICA) in 1984, which required the use of market research and procurement planning to promote the use of competitive procedures in federal contracting (GAO, 1996). Congress reemphasized the importance of market

research in 1990 with the National Defense Authorization Act for Fiscal Year (FY) 1991 (GAO, 1996). The act encouraged the DoD to save money and reduce cycle time by procuring commercial items. Furthermore, the Federal Acquisition Streamlining Act (FASA) posed additional requirements for market research when enacted in 1994 (GAO, 1996). The act required federal executive agencies to conduct market research before developing new specifications for a requirement and before soliciting proposals for a contract expected to exceed the simplified acquisition threshold. Additionally, the FASA requires that contracting officers use market research to determine whether commercial items or non-developmental items could meet their agency's needs if the requirement was modified to some extent.

DoDI 5000.2-R, Mandatory Procedures for Major Defense Acquisition Programs and Major Automated Information System Acquisition Programs (USD[AT&L], 2002), requires that market research and analysis be conducted to determine the availability and suitability of commercial and non-developmental items prior to the commencement of any development effort, during the development effort, and prior to the preparation of any product description (DoD, 1997). FAR Part 10 (2011) prescribes policies and procedures for conducting market research to arrive at the most suitable approach to acquiring, distributing, and supporting supplies and services (DoD, 1997).

The aforementioned laws and regulations require the accomplishment of market research. However, outside of a push for commercial items and services, the laws and regulations offer little in terms of the quality of market research and how this affects acquisition outcomes (in both pre- and post-award contracting decisions). The FAR (2011) offers little direction; Parts 10 and 12 dedicate a mere 1,477 words to the topic of market research. The DoD (1997), Air Force Logistics Management Agency (1997), National Aeronautics and Space Administration (NASA; 1998), and Headquarters, Air Force Material Command (HQ AFMC; 2007) developed market research guides; however, they are outdated and do not address market research needed to support strategic sourcing.

Government agencies rarely budget for commercially available market intelligence, and no existing policy addresses how to properly organize the collection and use of market intelligence. Furthermore, specific skills for finding, analyzing, and disseminating information are not systematically taught or developed in the government's acquisition workforce. However, a study of 30 large firms showed that business and market analysis is a necessary skill of a world-class purchaser (Giunipero, 2000).

Concerning market intelligence, there is a difference between compliance and effectiveness. Today, a contracting specialist can perform a cursory collection and documentation of market intelligence and be compliant with the FAR but at the same time, forego value due to the omission of key information. Clearly, mere compliance is insufficient. Given current fiscal constraints, the federal government is gradually elevating the importance of efficiency—one of several key goals of the federal acquisitions system (FAR Part 1.102, 2011). Smart, informed decisions in pre- and post-award contracting decisions strongly impact the efficiency of contracted outcomes. Market intelligence is the key to making better decisions that provide more value to the customer and to the taxpayer.

Market intelligence also contributes to the development of reliable cost estimates and budgets (Denali Group, 2009). The need for market intelligence does not stop upon contract award; it also supports the negotiation of post-award matters, such as changes and dispute resolution, and is essential throughout the life of the contract (Leenders, Johnson, Flynn & Fearon, 2006). Agencies must ensure that previously negotiated prices remain fair and reasonable prior to exercising options. The more critical, valuable, complex, and risky the procurement, the more important market intelligence becomes in order to craft a contract

that manages performance risk, maximizes contractor performance, balances financial risk to both parties, and meets agency needs. Figure 1 lists contracting processes that require valid and complete market intelligence in order for acquisition teams to make optimal business decisions.

1. The number and identity of capable suppliers 2. The number and identity of capable small business suppliers by socio-economic category 3. Cost drivers 4. The nature of customarily offered products and services	30. Appropriate supplier performance metrics 31. Engaging existing commercial logistics and maintenance support infrastructures to decrease total life-cycle support costs 32. Whether a reverse auction is appropriate 33. Required buyer financing
5. Current market costs and prices	34. Market discounts or rebates
6. Inflation/deflation rates	35. Applicable laws and regulations
7. Typical evaluation criteria used to discriminate between offers	36. Risks of particular suppliers based on their record of performance
8. The structure of the marketplace	37. Customary profit margins
9. Analysis of the industry	38. Typical overhead rates
10. Power positions of the prospective suppliers relative to the buyer	39. Existing government contracts 40. Identify conflicts of interest
11. Customary terms and conditions	41. Macro- and micro-economic indicators
12. Incentives that effectively motivate supplier performance	42. Improve spend analysis by identifying mergers and acquisitions
13. Customary payment terms	43. Production rates
14. Intellectual property rights	44. Assess supply and demand
15. Typical contract types	45. Labor rates
16. Contract line item structures	46. Inventories
17. Contract durations	47. Data needed for SWOT analysis
18. Customary surveillance methods and frequencies	48. Assess market share held by prospective suppliers
19. Typical service and performance levels	49. Supplier locations
20. Prospective supplier financial health	50. Supplier revenue models
21. Proactively addressing diminishing manufacturing sources and obsolete parts issues (HQ AFMC, 2007)	51. Manage subcontracts via subcontract consent, socio-economic goals, and contractor purchasing system reviews
22. Determining how attracted prospective suppliers are to the business	52. Whether expected savings will meet thresholds to justify bundling or consolidation
23. Price volatility	53. Supplier capacities
24. Energy conservation potential and the use of recoverable material	54. Optimizing best value acquisitions through competitive market pressures
25. Assessing the impacts of emerging technologies to enhance customer capabilities and potential system performance or reliability improvements 26. Definitions of requirements 27. Delivery lead times 28. The availability of commercial items and services	55. Evaluating the government's leverage in the market sector in terms of how extensively the government's requirements influence the available business opportunities and market trends in that sector 56. Whether performance-based contracts are used 57. Identification of best-in-class suppliers
29. Customary warranty terms	

Figure 1. Pre- and Post-Award Demands for Market Intelligence

Strategic sourcing is "a collaborative and structured process of analyzing an organization's spend and using the information to make business decisions about acquiring commodities and services more efficiently and effectively" (Office of Management and Budget [OMB], 2005). In strategic sourcing, requirements are aggregated, contract values are increased, customers per contract are increased, and suppliers are rationalized. Hence, complexity, value, risk, and importance increase with strategic sourcing. In order to save money, government acquisition members must focus more precisely on the cost drivers of the market, necessitating more robust intelligence.

Commercial sector firms have long recognized the importance of market intelligence to effective supply management. Successful market intelligence can become a firm's competitive advantage (Porteous, 2011). Many firms staff business intelligence cells that feed commodity councils with key information and data (Ashenbaum & Pannelle, 2007; Zsidisin, 2005). One firm saved $194 million through the collection and use of market intelligence (Zsidisin, 2005).

Literature Review

Market Research/Intelligence

Market research is the continuous process of collecting information (i.e., market intelligence) to maximize reliance on the commercial marketplace and to benefit from its capabilities, technologies, and competitive forces in meeting an agency's need (DoD, 2011). Market research is a vital means of arming the acquisition team with the expertise needed to conduct an effective acquisition. Market research gathers current data on existing market sectors to identify potential sources of supply, commercial product characteristics, market characteristics, commercial item standards and best practices, emerging technologies, vendor capabilities, non-developmental item solutions, and government leverage opportunities so that informed acquisition strategy decisions can be made (HQ AFMC, 2007). This market intelligence can be classified as two types: strategic or tactical.

- Strategic market intelligence (a.k.a., market surveillance) is an ongoing process, and includes activities that the acquisition team performs continuously to keep themselves abreast of changes in the marketplace, such as technological advances, process improvements, and available sources of supply. The purpose of market surveillance is to maintain a current knowledge base of the depth, breadth, and dynamics of the market sector (HQ AFMC, 2007).
- Tactical market intelligence (a.k.a., market investigation) is a comprehensive market research survey conducted in response to a specific acquisition or need. The purpose of market investigation is to collect supporting data and documentation to determine an appropriate acquisition strategy (HQ AFMC, 2007). The appropriate acquisition strategy may include pre- and post-award considerations. This may include the following: planning for new acquisitions, deciding to exercise an option, and determining the effects of key supplier mergers.

Theoretical Foundation

Information gathering, dissemination, and use are grounded in market orientation theory (Kohli & Jaworski, 1990). This theory depicts how firms collect information regarding customer needs, disseminate the information within the firm, and respond to the information by designing and offering products and services that meet customer needs. A meta-analysis of market orientation (Kirca, Jayachandran, & Bearden, 2005) shows that a market

orientation increases innovativeness. Innovativeness increases customer loyalty and quality which, in turn, increase organizational performance (profitability). In order to facilitate information gathering, dissemination, and use, organizations need top-management support, supporting interdepartmental dynamics, and supporting organization-wide systems. Departmentalization, formalization, and centralization hinder intelligence generation, dissemination, and response. These are strong characteristics of government organizations, which might hinder their effective use of market intelligence.

Firms can also benefit from collecting and using information from suppliers. “A supply chain orientation is defined as the extent to which there is a predisposition among chain members toward viewing the supply chain as an integrated entity and on satisfying chain needs in an integrated way” (Hult, Ketchen, Adams, & Mena, 2008, p. 527). Such information might include supplier capabilities, capacities, constraints, risks, strategic plans, and costs. Using the same processes as market orientation—information collection, dissemination, and response—a buying firm can improve its performance (customer performance, financial performance, internal process performance, and innovation and learning performance), as was shown in a study of 129 firms by Hult et al. (2008). Essentially, this is what the government does with market intelligence—optimizing the requirement definition (i.e., the need) by discovering what is available in the market instead of defining needs based on what was done in the past. The government has an opportunity to improve performance by collecting the market research, disseminating it within the agency, and making appropriate decisions by acting upon the available information. All of this presupposes that we collect the right information and make wise decisions from it. In that vein, the government can enhance credibility by using market intelligence to drive acquisition strategies.

New Approaches to Market Intelligence

A New Paradigm

MR/MI operates within and through three distinct dimensions: the need, the environment, and the plan. The *need* is the definition of the government’s requirement and is sought and found in three particular ways: (1) what we think we need based on previous buying history or limited explanation, (2) what we actually need manifested as the final evolved requirement through the long government acquisition process, and (3) the optimal choice we are unaware of or what we could have asked for if we had understood our environmental dimension.

The *environment* is the business and “battlespace” in which the government operates, and is composed of many factors. Some of these factors include the industry, the area of responsibility, political arena, industry analysis, capabilities, standards, and risks. The environment also consists of socio-economic issues and policies, as well as external considerations and risks (e.g., legislation, national conflict, geography, etc.).

The *plan* is the government’s strategy for how it satisfies its needs within its environment, including, but not limited to, the acquisition strategy/plan, source selection plan, and small business plan. The current model is a serial process that involves the government doing the following:

- **Step 1:** Determine the need that is pushed by the user, checked against current supplies and previous purchases, and evolved over time (amendments/changes).

- **Step 2:** Assess the environment by reviewing vendor lists, seeing where our funds are spent, posting requests for information, and consulting the Small Business Administration (SBA).
- **Step 3:** Develop the plan, such as acquisition plans, by holding acquisition strategy panels, creating evaluation and incentive criteria, determining contract types and structures, coordinating with the SBA, producing government estimates and performance plans (e.g., quality assurance surveillance plan), and making option determinations.

The current model offers "too little, too late." The current approach takes a reactionary approach often resulting in defining the need before optimizing the potential solution. Further, we follow a serial approach in a business environment that is not linear. It is global, multi-dimensional, and evolving faster than we can react. We decide the need before we know our environment, and the need starts to change as we develop our plan but we do not reassess the environment. When we use immediate needs to drive MR/MI, we rarely commit time to reassess. Finally, the current model does not meet the intent of FAR (2011) Subpart 10.001(a) to conduct market research on an on-going basis. Current practice is to conduct market research as an initial step to acquisition planning that is done at the beginning and not monitored after the fact.

The proposed model (see Figure 2) recognizes three distinct dimensions to be assessed simultaneously and continuously, while maintaining a high level of education and training. The *need* dimension involves having early talks with management, leadership, approving offices, technical SMEs—as with an early strategy and issues session (ESIS)—and functional users 12 to 24 months prior to an anticipated award. Further, the *need* dimension involves maintaining a robust spend analysis of current contract portfolios with informed projections for future portfolios, using tools such as a purchasing portfolio model to segment spend by type (Kraljic, 1983). It further involves understanding agency tendencies and constraints using tools such as a strengths, weaknesses, opportunities, and threats (SWOT) analysis.

The environment dimension involves holding industry days and issuing requests for information (RFI) periodically to monitor new entrants, market trends, bundling/consolidation issues, and possibilities. Other considerations include Porter's (1979) five forces analysis, a power-matrix analysis (Cox, 2001), and a risk analysis (cost, technology, performance), and capturing market cost drivers while assessing regulation, standards, and commercial practice. Finally, the environment dimension must consider monitoring external issues such as national political trends and legal and regulatory developments.

The proposed model introduces the concept of an education and training (E&T) cycle, the idea being that all market intelligence collected during the continual processes over time is shaped by previous and current education and training, and must shape future MR/MI efforts and improve education and training.

Figure 2. Proposed Model of Perpetual Market Research

Under the proposed model, the MR/MI process is a synergistic process that combines all dimensions, and assesses how to optimize needs in a changing environment. This proposed model directs our focus to the changing environment and being proactive instead of focusing on reactive, short-term needs. Acknowledging an increasingly-rapid pace of changes to our environment, and recognizing the evolving primacy of efficiency as a critical acquisition outcome, the value of this proposed model of MR/MI becomes apparent. This value can be demonstrated in many steps and activities of the strategic sourcing process. The following sections elaborate on three activities in which MR/MI offers opportunities for improved acquisition outcomes: goal setting and opportunity assessment, strategic cost management, and consolidation/bundling.

Goal Setting and Opportunity Assessment

Purchasing (i.e., supply management) is a strategic activity (Carter & Narasimhan, 1996) due to its ability to contribute to a firm's competitive advantage (Ellram & Carr, 1994). Two of the most important and implemented aspects of strategic supply management are strategic planning and performance measurement (Monczka & Petersen, 2008). Firms that develop supply management strategic plans typically set three-to-five year outlooks with goals linked to key performance indicators. Progress toward goals is measured as often as twice per month. It is often said that what gets measured, gets done, and that metrics drive behavior. Supply management leaders are responsible for setting and achieving appropriate sourcing goals, and such goals should feed into the organization's overall goals and strategies. These goals and metrics focus commodity councils on what is important. Goals should be specific, measurable, attainable, relevant, and timed (Rudzki, Smock, Katzorke, & Stewart, 2006).

But how does a commodity director know whether his or her savings, efficiency, and effectiveness goals are attainable? Market intelligence plays a pinnacle role. First, an organization should benchmark its performance against its competitors and against best-in-class organizations (Rudzki et al., 2006). Reports, data, and benchmarks are often available from sources, such as AT Kearney, McKinsey, Aberdeen Group, CAPS Research, Sourcing Interest Group, Gartner Group, IBISWorld, Forrester, Market Reports Online,

MarketResearch.com, Research and Markets, consultants, and various industry-specific trade associations. Participating in electronic reverse auctions (eRA) and buying consortia also unveil current pricing information. Second, routine comparisons to historical prices paid should be made. If the procuring contracting officer were asked the current prices paid, would he or she be able to respond without opening the contract file? Third, prices could be compared to the producer price index available from the U.S. Bureau of Labor Statistics. However, note that this index is not always sufficiently precise (Rudzki et al., 2006).

Rudzki et al. (2006) offered general ranges of savings by type of spend (see Table 1). These benchmarks can be used not only to set goals for a commodity council but for specific requirements as well. Note that these levels of savings are not unique to the for-profit sector. Government buyers have achieved nearly double the savings (28%) compared to their for-profit sector counterparts on sourcing improvement projects (Husted & Reinecke, 2009). There appears to be ample opportunity for the government to improve.

Often, organizations will have more requirements to source than resources available to source them strategically. In this case, strategic sourcing organizations must prioritize sourcing events (i.e., requirements). One tool to facilitate these decisions is an opportunity assessment. Here, each requirement is assessed in terms of *the degree of difficulty of implementation and savings and/or performance impact* (Monczka & Petersen, 2008). Obviously, those requirements that are easier to implement yet yield substantial savings will be sourced first. The important point here is that the savings potential cannot be validly estimated without solid market intelligence that unveils opportunities to alter strategies. This requires near-constant market surveillance and deep category expertise. High turnover will cripple the ability to collect, disseminate, and act upon market intelligence, that is, to know the market.

Table 1. Savings Opportunity by Type of Spend

Type of Spend	Potential Savings (% of total spend)
Raw materials	2–5
Packaging	10–20
Indirect materials and services	10–20
Information technology	15–30
Professional services	8–15
Logistics	7–15
Media/marketing/promotional items	10–20
Other indirects	5–15
Capital projects	7–15

Strategic Cost Management

An important tenet of strategic sourcing is strategic cost management (Monczka & Petersen, 2008, p. 43), defined as “the identification and proactive management of all costs and associated cost drivers throughout the product/service supply chain.” It “requires development, prioritization and implementation of strategies and processes to control, reduce or eliminate costs during each phase of the life cycle” (Monczka & Petersen, 2008, p.

43). Strategic cost management offers substantial opportunities for cost savings and cost avoidance, as illuminated in the following three examples. As evidenced in these examples, market intelligence is essential to identify, quantify, and understand cost drivers.

The first example concerns elevator maintenance services. The Air Force's Enterprise Sourcing Group conducted extensive market research in 2011 (HQ AFMC, 2011). Figure 3 shows elevator maintenance cost drivers provided by IBIS World, a leader in syndicated market research. Labor and profit account for the majority of costs (Ripley, 2011). Employee compensation declined while industry profitability peaked at 29% in 2008 (Ripley, 2011). Compared to similar industries, there may be opportunity to negotiate a lower margin. A comparison of historical rates to prevailing market rates revealed that the Air Force was paying 18–20% more than other federal and commercial clients (HQ AFMC, 2011).

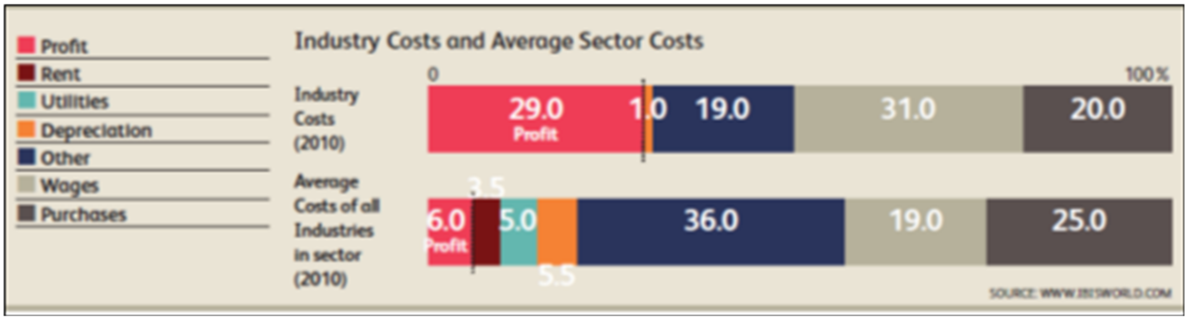

Figure 3. Industry Cost Breakout

Prices depend on cost drivers, such as the number of units, type of equipment, age of equipment, manufacturer, equipment usage, desired service call frequency, and location of equipment. Prices differ significantly by equipment types. Because traction elevators contain more moving parts and maintenance requirements than do hydraulic elevators, their cost is two to three times higher. Additionally, equipment age is highly correlated with the degree of required maintenance and repair. The Air Force's oldest elevator equipment is 60 years old, with an average age of approximately 20 years. The equipment manufacturers also drive costs. A contractor may charge more to service a wide variety of equipment. Contractors seek to offset the risks of obsolescence costs from servicing equipment from manufacturers that are no longer in business. The frequency of service calls affects pricing as well. Customers requiring more frequent service incur greater cost due the need for on-site technician time and associated travel expenses. A growing trend in the industry is usage-based service rather than regularly scheduled maintenance. Relatively low usage by the Air Force could yield cost savings by converting to demand-based versus time-based service (HQ AFMC, 2011).

As a second example, consider a Fortune 500 firm that outsourced the supply and management of its service vehicle fleet. The total cost of ownership breakdown (see Figure 4) reveals the major cost categories to be the lease expense, fuel, and vehicle maintenance. However, the underlying cost drivers were the quantities, ages, types of vehicles, depreciation rates, cost of capital, miles driven, cost per barrel of oil, vehicle condition, and maintenance labor and parts. Most government acquisition professionals would look to minimize the major cost categories but often overlook a deeper investigation of underlying cost drivers. For example, a contracting officer might leverage competition to reduce the cost of capital, or, again via competition, might influence offerors to seek the most cost-effective national maintenance network. However, they may overlook other opportunities for cost avoidance via tenets of strategic sourcing, such as demand management and e-

sourcing. For example, prior to the vehicle strategic sourcing event, the internal customer defined the fleet needs as in the past: The firm needed 2,600 service vans. By staying abreast of developments in the market, an astute commodity manager discovered that an auto manufacturer altered its strategy to sell one of its models. This model did not sell well in the consumer market (Kiley, 2005); thus, the manufacturer repositioned it as a fleet vehicle—at a steep discount compared to traditional vans. By collecting this market intelligence, disseminating it within the user community, and acting upon it (i.e., switching vehicle types), the commodity manager saved approximately $1 million on its $23 million fleet spend. Hypothetically, using another savings lever, the commodity manager could require the fleet management contractor to source its fleet vehicles from manufacturers using electronic reverse auctions (eRA), an e-commerce tool that typically saves buyers 20% (Cohn, Brady, & Welch, 2000) via online, real-time competition (Hawkins, Randall, & Wittmann, 2009).

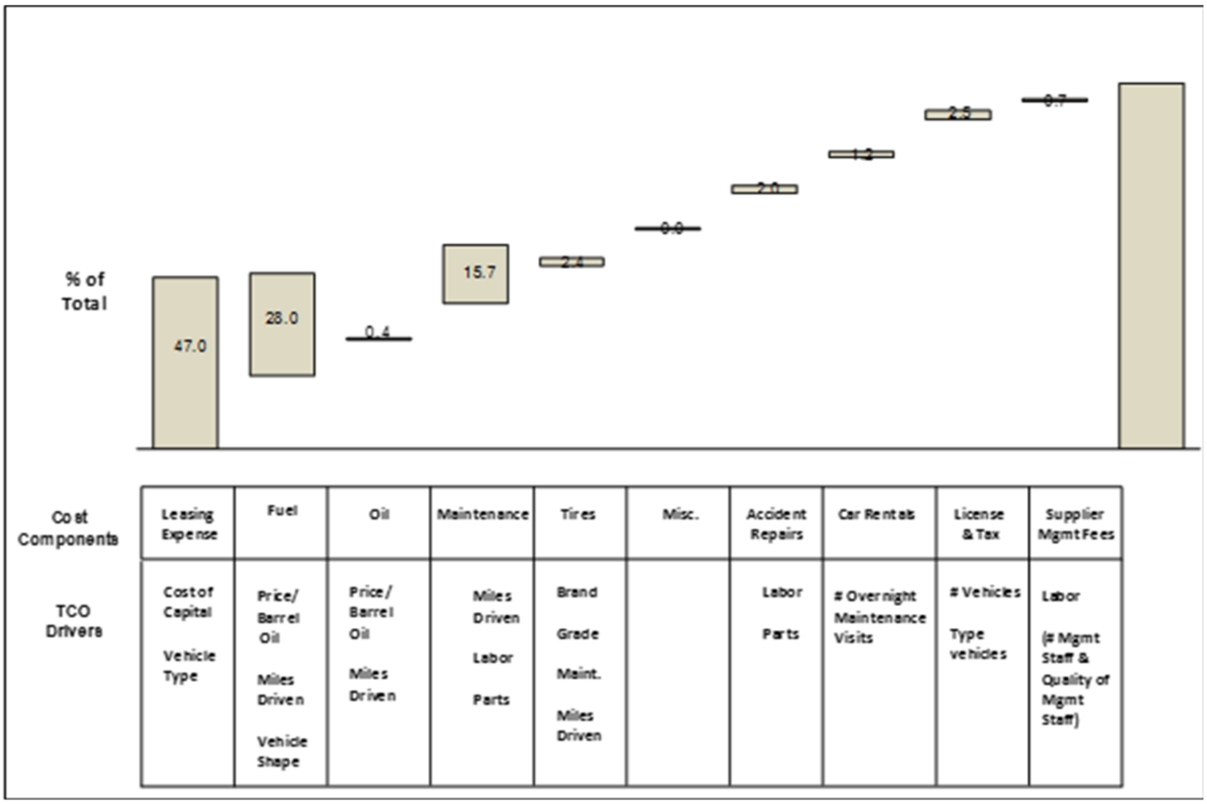

Figure 4. Vehicle Fleet Total Cost of Ownership Analysis

As a final example, consider the Air Force's attempt to strategically source security guard services at 29 installations in 2004 (Bowman, Reed, Hudgens, & Searle, 2006). The major cost category was labor. The savings lever sought was economies of scale by consolidating separate contracts at several installations. However, rigidity of the major cost driver was overlooked. The labor rates were subject to the Service Contract Act of 1965; thus, the Department of Labor established minimum wage rates via wage determinations (based on average wages in each locale). These wage rates remained constant regardless of the number of employees hired under a single contract. Thus, while transaction costs were somewhat reduced, the resultant contract failed to yield meaningful savings from economies of scale. These three examples highlight the importance of market intelligence in strategic cost management.

Consolidation Strategies and Socio-Economic Support

MR/MI proves critical to bundling and consolidation procurement strategies. Both bundling and consolidation aggregate requirements to (1) achieve volume savings from the marketplace, (2) reduce transaction costs associated with multiple source selections and multiple contracts, and (3) reduce performance risks associated with managing a greater variance of performance across more suppliers. FAR (2011) Subpart 2.101 defines *bundling* as consolidating two or more requirements for supplies or services, previously provided or performed under separate smaller contracts, into a solicitation for a single contract that is likely to be unsuitable for award to a small business concern.

DFARS (2011) Subpart 207.170-2 defines *consolidation* of requirements as

> the use of a solicitation to obtain offers for a single contract or a multiple award contract to satisfy two or more requirements of a department, agency, or activity for supplies or services that previously have been provided to, or performed for, that department, agency, or activity under two or more separate contracts.

Consolidation or bundling of requirements increases the scope of work performed by the contractor. Because a firm's revenue or number of employees determines its small business designation within its industry, the increased scope can make it more difficult to obtain competitive offers from two or more small businesses. Subsequently, consolidated or bundled procurement solicitations may go out as *unrestricted*, requiring small businesses to compete directly with large businesses.

FAR (2011) Subpart 7.107 specifically addresses bundling contract actions as they relate to small business. In order to bundle requirements, the government must ensure that it considers the impact on small business participation and the measurable benefits of bundling (e.g., quality improvements, administrative or direct cost savings, etc.). Additionally, FAR (2011) Subpart 7.107(a) states that "because of the potential impact on small business participation, the head of the agency must conduct market research to determine whether bundling is necessary and justified." The FAR establishes minimum percentage savings thresholds for bundling to balance the government's cost efficiency goals with socio-economic goals. According to FAR (2011) Subpart 7.107(b), the agency may justify bundling as compared to the benefits that it would derive from contracting to meet those requirements separately if it results in savings equal to or greater than

> (1) ten percent of the estimated contract or order value (including option) if the value is $94 million or less; or (2) five percent of the estimated contract or order value (including options) or $9.4 million, whichever is greater, if the value exceeds $94 million.

Due to the perceived negative impact to small business, bundling and consolidation are politically sensitive, to say the least. Any savings estimates will likely be scrutinized. MR/MI provides the key information required to quantify and substantiate the realistic savings potential. Although a solid business case may justify bundling or consolidation, such a strategy may be perceived as politically untenable. Nevertheless, compelling savings and performance improvement opportunities may open avenues to compromises (e.g., consolidated or bundled small business set asides, partial small business set-asides, or requirement offsets) that offer a win-win outcome.

The FAR and DFARS are very specific in their requirements for bundling contracts to minimize the impact on small businesses. However, while the information required is clear, the methods of collection are ambiguous. Examining current and past contracts, contracts of

other agencies, industry best practices, academic articles; attending conferences; or conferring with third party consultants are all valid methods of data collection. The amount of evidence necessary to substantiate cost savings will rely on the amount required by the Head of Contracting Activity. Additional considerations may exist within the industry or market further limiting bundling. All these issues must be considered when performing market research to bundle or consolidate contracts. MR/MI is pivotal in determining whether a small business can provide the desired product or service.

An example was the Air Force's Furnishings Commodity Council (AFFCC) in 2009. The AFFCC utilized MR/MI to identify industry best practices, benchmarked those best practices, and created business cases for cost savings initiatives. To identify the savings opportunity for each business case, the AFFCC used a percentage-of-savings methodology based on government and commercial savings benchmarks, historical Air Force spend analysis from FY2000 to FY2007, and furnishings market forecast information.

The AFFCC relied heavily on a spend analysis to determine historical spend data on which to base the savings estimates. Based on the historical spend, the AFFCC was able to forecast spend data from 2009 to 2013. The results of the spend analysis showed that over 76% of furniture purchases were made from small businesses. Additionally, market research showed that over 50% of an office furniture manufacturer's cost structure was variable, and that labor made up the majority of fixed costs. This led the AFFCC to the volume purchasing sourcing strategy. The market research showed that manufacturers are attracted to volume purchases due to the ability to lower cost by fully utilizing labor, which is the second largest component of furniture cost. As a result, the AFFCC utilized industry benchmarks from government and commercial sources to estimate five-year savings within three categories: conservative (3%), moderate (6%), and aggressive (9%; Air Mobility Command [AMC], 2009).

The three savings estimate categories were applied to three business cases to show cost savings. The business cases included the following savings levers: develop Air Force furnishing standards and supporting policy (standardization); develop centralized contract vehicles (leverage volume to drive price reductions and improve purchasing efficiency); and acquire comprehensive furniture management services consisting of seven categories to include project management, asset management, reconfiguration/relocation management, space planning and design, packaged furnishings, asset maintenance, and site preparation and reconfiguration (AMC, 2009). The market research enabled the AFFCC to conclude that over a five-year period, furniture standardization, a centralized contract vehicle, and comprehensive furniture management services savings combine for an estimated cost savings between 10.6 to 215 or $41.2 million to $81.8 million, respectively (AMC, 2009). The conservative estimates of savings exceeded the thresholds necessary for bundling and consolidation.

The commodity team's goal was to reduce life-cycle costs, eliminate duplicate efforts, standardize requirements, and lower total ownership costs. The AFFCC created a standardized requirements list for all bases. This list included basic specifications for different types of office chairs such as executive, executive guest, and side/general seating. Each requirement also had a minimum warranty that vendors would have to guarantee. The idea was to make the requirements as basic as possible and to allow suppliers to quote various options. Once they identified what the requirements would be, the AFFCC began to research the available furniture vendors in the market.

Most of the furniture manufacturers, large and small, used furniture dealers to market and sell their products. Most of these dealers are small businesses located throughout the

country. Manufacturers typically do not have their own showrooms. Some dealers only specialize in certain manufacturers' brands, but for the most part, dealers represent all manufacturers. One of the methods used to gain vendor awareness was the National Exposition of Contract Furnishings (NEOCONs) world's trade fair in Chicago. Participants of the trade show learn about the latest designs, trends in fashion, and scientific breakthroughs in chair ergonomics.

Through further research and the help of consulting firms, the Air Force determined that 63% of furniture manufacturing was done by the "Big Five" companies. An RFI was posted in 2007, and 41 responses were received. Most of the distributors proposed teaming agreements with large manufacturers. In 2008, members of the AFFCC attended the 2008 NEOCON. The teams also learned what each manufacturer's production capacity was and whether they could handle the increased capacity of supplying the Air Force.

After thorough market analysis and research, the AFFCC determined that the commercial marketplace could fulfill the Air Force's needs, and that the seating products offered via the GSA schedule met the minimum requirements. Through spend analysis, the Air Force Small Business Solution Center (AFSBSC) identified that only 23% of the suppliers of office furniture were small business non-GSA manufacturers (AFSBSC, 2009b). However, the AFSBSC found that wood seating comprised of mostly niche small business manufacturers (AFSBSC, 2009b). In addition, the Air Force bought 80% of dorm furnishings from small businesses (AFSBSC, 2009a). Thus, it was determined that even with consolidation, the AFFCC would receive adequate small business competition for Spiral 1 (wood seating) and Spiral 1A (dorm furnishings). Extensive MR/MI gave the AFFCC current market condition information necessary to make an informed and substantiated small business participation determination for some wood seating and dorm furnishings while supporting consolidation for office furniture.

Conclusion

The importance of thorough MR/MI cannot be overstated. MR/MI informs both pre- and post-award processes and decisions, and therefore has a direct, lasting impact on the quality of the product or service the government receives and the price it pays. The primary purposes of MR/MI are to arm the acquisition team with an accurate picture of the state of industry, to help assess the feasibility of varying procurement options, to optimize value and mitigate costs, to identify potential sources of supply and services, to identify and mitigate risks, and to be cognizant of similar historical procurements.

A handful of guides and tools to aid in the conduct of market research exist, but they are lacking in one or more respects—they are either vague or lacking sufficient detail or examples, more prescriptive than descriptive, too lengthy—and therefore not used and often ignored by the majority of acquisition professionals. In recognition of these weaknesses, the Naval Postgraduate School recently published the most comprehensive market research guide to date (Hawkins et al., 2012).

Furthermore, government acquisition personnel tend to follow a "needs-based" archetype for market research. The acquisition team first determines the need by working with the user to refine the definition of the requirement to come to a common understanding in a process known as "requirements definition," and then cross-checks the need against existing sources of supplies or contracts, vendor lists, and previous purchases, as well as consulting with the small business office as applicable. When the initial market research is complete, the team should use the information acquired to develop the acquisition plan and to create a suitable contract structure based on appropriate evaluation criteria relevant to

the acquisition. When properly applied, market research is a powerful pre-award tool, although market research should not stop after the award of a contract.

Market research is an iterative process and should be applied over the entire life cycle of an acquisition. Rather than a reactive stance to MR/MI, a more optimal solution involves a continual, proactive approach that yields better contracts and more fluent contract administration, and that provides acquisition teams the leverage they need to obtain the best value for the government. To obtain the benefits of MR/MI, a shift in the current culture of acquisition professionals is required.

Historically, anecdotal evidence shows that far too often, market research is underscored by limited effort and documentation to comply with the general requirement to conduct it as mandated by the FAR, which results in another box to check on a lengthy list of mandated pre-award tasks. Fully realized, MR/MI can better inform critical acquisition processes (see Figure 1) such that the government realizes meaningful differences in needed outcomes. This leads to the following recommendations.

Recommendations

To become proficient at gathering, disseminating, and responding to market intelligence, greater attention is needed. Currently, market research is a stepchild in federal acquisition; it is not resourced commensurate with its importance in affecting contracted needs. Therefore, we offer a short list of ideas to enable a stronger infusion of market intelligence into outcome-driven acquisition decisions.

- Create a central repository of market reports and information searchable by NAICS code and by date. This will help acquisition teams share gained knowledge and prevent the duplication of effort. The Air Force had an on-line market research repository system known as MRPost. MRPost was a good idea, but it was not utilized because (1) policy did not enforce usage, (2) it was not publicized well enough to users, or (3) the users viewed it as just another task to perform instead of a valuable source of information.
- As Handfield (2006) recommended, stand up a central market intelligence cell staffed with experts in certain industries who are available to generate market analyses to acquisition teams.
- Budget for market intelligence, such as that found in syndicated and customized market reports (e.g., Gartner Group, Hoovers, Dun and Bradstreet Supplier reports, IBISWorld, and the Sourcing Interest Group).
- Develop a course available from the Defense Acquisition University that teaches best practices in market research by walking the students through a case study where market intelligence made the difference in efficiency and effective contractor performance.

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Acquisition Portfolio Trends

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The GAO's 11th Annual Assessment of Selected Weapon Programs

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Weapons Acquisition Reform: Reform Act Is Helping DoD Acquisition Programs Reduce Risk, but Implementation Challenges Remain

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Introduction

For several decades, the GAO has reported on poor outcomes encompassing cost and schedule growth on the Department of Defense's (DoD's) major weapon acquisition programs. Many problems can be traced to a culture where the military services begin programs with inflexible requirements, immature technologies, and overly optimistic cost and schedule estimates. Given pressures to reduce spending across the government, including the DoD, finding ways to prevent or mitigate cost growth is crucial to U.S. national security. A solid program foundation using good developmental testing and systems engineering, and reliable cost estimates is needed in order to help avoid cost overruns and promote better acquisition outcomes. There have been numerous attempts in the past to improve DoD acquisition outcomes, including the Packard Commission (President's Blue Ribbon Commission on Defense Management, 1986), the Goldwater–Nichols Act in the 1980s (1986), and the Federal Acquisition Streamlining Act of 1994. More recently, Congress passed the Weapon Systems Acquisition Reform Act of 2009 (Reform Act)[1] to improve the way weapon systems are acquired and avoid cost and schedule overruns.

In 2009, the Senate Armed Services Committee asked us to begin reporting on the DoD's implementation of Reform Act provisions and the impact the Reform Act has had on weapon acquisition programs. This is our third report addressing these topics. The first report focused on the DoD's initial efforts to implement Reform Act provisions for systems engineering and developmental testing, including the placement of new offices for these activities within the Office of the Secretary of Defense (OSD; GAO, 2010). Our second report examined the challenges the Services face as they try to strengthen systems engineering and developmental testing activities on weapon acquisition programs (GAO,

[1] As amended by the Ike Skelton National Defense Authorization Act for Fiscal Year 2011, Pub. L. No. 111-383 §§ 813 and 1075, and the National Defense Authorization Act for Fiscal Year 2012, Pub. L. No. 112-81 §§ 819 and 837.

2011b). This report examines (1) the DoD’s progress in implementing Reform Act provisions; (2) the impact the Reform Act has had on specific acquisition programs; and (3) challenges remaining in improving the weapons acquisition process.

We conducted this performance audit from January 2012 to December 2012 in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

Background

In May 2009, Congress passed the Reform Act in an effort to improve the way weapon systems are acquired and avoid further cost overruns on such programs. When signing the Reform Act into law, the President stated that its purpose was to limit weapon system cost overruns and that it would strengthen oversight and accountability by appointing officials who will closely monitor the weapons systems acquisition process to ensure that costs are controlled.

Four offices were established as a result of the Reform Act: SE, DT&E, CAPE, and PARCA. The SE and CAPE offices existed under other organizational titles prior to the Reform Act. Staffing levels, following the Reform Act, remained relatively stable for both of these offices, but some reorganization was necessary to reflect new Reform Act responsibilities. The DT&E and PARCA offices were newly established. The key roles and responsibilities of these four offices as outlined in the Reform Act are explained in Table 1.

Table 1. Key Responsibilities of Offices Established as a Result of the Reform Act

Office	Primary responsibilities
Systems Engineering	• serves as principal advisor to the Secretary of Defense and the Under Secretary of Defense for Acquisition, Technology, and Logistics on systems engineering activities in the department • develops systems engineering and development planning guidance for the DoD • reviews and approves major defense acquisition program systems engineering plans • monitors major defense acquisition program systems engineering activities • reports to Congress annually on systems engineering organization, capabilities, and activities
Developmental Test and Evaluation	• serves as principal advisor to the Secretary of Defense and the Under Secretary of Defense for Acquisition, Technology, and Logistics on developmental test and evaluation activities • develops developmental test and evaluation guidance for the DoD • reviews and approves major defense acquisition program developmental test and evaluation plans • monitors and reviews acquisition program developmental test and evaluation activities of major defense acquisition programs • reports to Congress annually on developmental test and evaluation organization, capabilities, and activities
Cost Assessment and Program Evaluation	• serves as principal advisor to the Secretary of Defense and other senior officials on matters related to cost analysis and the planning and programming phases of the planning, programming, budgeting, and execution system • develops independent cost estimates for major defense acquisition programs prior to major milestone decisions and updates independent cost estimates when programs have exceeded critical cost thresholds, known as Nunn–McCurdy breaches • reviews existing systems and methods for tracking and assessing operation and support costs on major defense acquisition programs • develops analysis of alternative study guidance for major defense acquisition programs • approves the analysis of alternatives study plan for each major defense acquisition program
Performance Assessments and Root Cause Analyses	• assesses major acquisition program performance through independent analyses and through the Defense Acquisition Executive Summary process • identifies the root causes of cost growth and other problems on programs that experience a critical Nunn–McCurdy cost breach

Note. This table was created using GAO analysis of the Weapon Systems Acquisition Reform Act of 2009.

In addition to the new organizational requirements, the Reform Act requires the DoD to ensure that the acquisition strategy for major defense acquisition programs includes measures to ensure competition or the option of competition throughout the program life cycle. This could include strategies such as maintaining two sources for a system (dual-sourcing) and breaking requirements for supplies or services previously provided or performed under a single contract into separate smaller contracts (unbundling of contracts; Weapon Systems Acquisition Reform Act of 2009, § 202). Major defense acquisition programs are also required to provide for competitive prototyping—where two or more competing teams produce prototypes before a design is selected for further development—prior to Milestone B unless a waiver is properly granted by the milestone decision authority

(Weapon Systems Acquisition Reform Act of 2009, § 202(a)),[2] and to meet the following Milestone B certification requirements, including:[3]

- Appropriate trade-offs among cost, schedule, and performance objectives have been made to ensure the program is affordable;
- A preliminary design review and formal post-preliminary design review assessment have been conducted and on the basis of such assessment the program demonstrates a high likelihood of accomplishing its intended mission;
- Technology has been demonstrated in a relevant environment on the basis of an independent review and assessment by the Assistant Secretary of Defense for Research and Engineering;
- Reasonable cost and schedule estimates have been developed to execute, with concurrence of the Director of CAPE, the program's product development and production plan;
- Funding is available to execute the program's product development and production plan;
- The DoD has completed an analysis of alternatives with respect to the program; and
- The Joint Requirements Oversight Council[4] has approved program requirements, including an analysis of the operational requirements.

The Reform Act also requires the Joint Requirements Oversight Council to ensure trade-offs among cost, schedule, and performance objectives are considered for joint military requirements (Weapon Systems Acquisition Reform Act of 2009, § 201). The GAO previously reported that the Council considered trade-offs made by the military services before validating requirements, but the military services did not consistently provide high-quality resource estimates to the Council for proposed programs in fiscal year 2010. We also found that the Council did not prioritize requirements, consider redundancies across proposed programs, or prioritize and analyze capability gaps in a consistent manner (GAO, 2011a).

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[2] Specifically, the Reform Act required the DoD to modify its guidance relating to the operation of its acquisition system to incorporate these competitive prototyping provisions. The DoD did so through Directive-Type Memorandum (DTM) 09-027, *Implementation of Weapon System Acquisition Reform Act of 2009* (Dec. 4, 2009, incorporating Change 3, Dec. 9, 2011). Major defense acquisition programs are those estimated by the DoD to require an eventual total expenditure for research, development, test, and evaluation, including all planned increments, of more than $365 million, or for procurement, including all planned increments, of more than $2.19 billion in fiscal year 2000 constant dollars or designated by the USD(AT&L). The Milestone Decision Authority for major defense acquisition programs is the USD(AT&L), the head of a DoD component, or if delegated the component acquisition executive.

[3] Pub. L. No. 111-23; various sections, codified at 10 U.S.C. § 2366b. The Reform Act revised the Milestone B certification requirements for trade-offs, preliminary design, technology demonstration, and reasonable cost and schedule estimates. The remaining Milestone B certification requirements bulleted here were unrevised by the Reform Act.

[4] The Joint Requirements Oversight Council is an advisory council to the Chairman of the Joint Chiefs of Staff with the responsibility to: (1) identify, assess, and approve joint military requirements; (2) assist acquisition officials in identifying alternatives to acquisition programs; and (3) assist the Chairman of the Joint Chiefs of Staff in assigning priority for joint military requirements.

Findings

The GAO's analysis of 11 weapon acquisition programs showed the Reform Act has reinforced early attention to requirements, cost and schedule estimates, testing, and reliability. For example, prior to starting development, an independent review team raised concerns about the Ground Combat Vehicle program's many requirements and the risks associated with its seven-year schedule. Subsequently, the Army reduced the number of requirements by about 25% and prioritized them, giving contractors more flexibility in designing solutions. In addition, the developmental test and evaluation office—resulting from the Reform Act—used test results to help the Joint Light Tactical Vehicle program develop a more realistic reliability goal and a better approach to reach it. Shown in Table 2 are areas where the Reform Act influenced several programs in the GAO's review.

Table 2. Reform Act Influence on Case Study Programs

Program	Requirements	Cost and schedule	Testing	Reliability
Before Milestone B				
Ground Combat Vehicle	✓	✓	✓	✓
Joint Light Tactical Vehicle[a]	✓	✓	✓	✓
Ohio Class Replacement	✓	✓	✓	✓
Ship to Shore Connector[a]			✓	✓
After Milestone B				
Joint Strike Fighter		✓		
Global Hawk		✓	✓	✓
Gray Eagle	✓	✓	✓	✓
KC-46 Tanker			✓	✓
Littoral Combat Ship Seaframe		✓		
Remote Minehunting System		✓	✓	✓
Small Diameter Bomb II		✓	✓	✓

Notes. This table was created using GAO analysis of DoD data.

[a] During the course of our review, the Joint Light Tactical Vehicle and Ship to Shore Connector programs held a Milestone B review.

While the DoD has taken steps to implement most of the fundamental Reform Act provisions, some key efforts to date have been primarily focused on the DoD's largest weapon acquisition programs. The DoD faces five challenges—organizational capability constraints, the need for additional guidance on cost estimating and Reform Act implementation, the uncertainty about the sufficiency of systems engineering and developmental testing resources, limited dissemination of lessons learned, and cultural barriers between the Office of the Secretary of Defense (OSD) and the military services—that limit its ability to broaden the Reform Act's influence to more programs. Service officials believe additional guidance is needed to improve their cost estimates and other implementation efforts. They also believe that lessons learned from programs that experience significant cost and schedule increases should be shared more broadly within the acquisition community. These challenges seem straightforward to address, but they may require more resources, which have been difficult to obtain. Ensuring the services have key leaders and staff dedicated to systems engineering and developmental testing activities, such as chief engineers at the service level and technical leads on programs, as well as breaking down cultural barriers are more difficult to address. They will require continued

monitoring and attention by the USD(AT&L), service acquisition executives, and offices established as a result of the Reform Act to address.

Recommendations

The GAO recommends the DoD develop additional cost estimating and Reform Act implementation guidance; make lessons learned available to the acquisition community; and assess the adequacy of the military services' systems engineering and developmental testing workforce. The DoD generally concurred with the recommendations. The GAO clarified one recommendation to make it clear that the DoD needs to designate an office(s) within the Acquisition, Technology, and Logistics organization to provide practical Reform Act implementation guidance to program offices.

For a more detailed discussion of our findings, as well as our scope and methodology, see www.gao.gov/products/gao-13-103.

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Service-Oriented Architecture Afloat: A Capabilities-Based Prioritization Scheme

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Abstract

To increase combat effectiveness by networking the warfighter and to easily modify and expand its existing network architecture, the United States Navy requires shipboard computer systems that are network-centric and service-based and that support open architectures. However, they are limited by the radio frequency bandwidth that is available for shipboard communications. As a result, some network applications must take priority over others. The current Navy prioritization scheme was not designed with the needs of the warfighter as the primary focus nor does it allow for dynamically changing priorities based on changing threats. A prioritization scheme is proposed that optimizes network performance based on warfighter needs. The scheme is developed using the Capabilities-Based Competency Assessment process introduced by Suttie & Potter (2008) applied to an air detect-to-engage scenario for a carrier strike group underway. A comparison is made between the proposed prioritization scheme and traditional Navy schemes using simulation. Results show our prioritization scheme consistently reduced latency and increased throughput for mission relevant applications. These improvements translate directly to more relevant information getting to decision-makers sooner, which leads to "information superiority," ultimately enhancing warfighting capability.

Introduction

The Program Executive Office for Command, Control, Communications, Computers, and Intelligence (PEO C4I) Masterplan summarizes the major programs of the Department of the Navy (DoN) applicable to network operations, providing outlines of planned future capabilities, their major characteristics, and timelines for their implementation. It includes a mandate for fielded computer systems to be network-centric, service-based, and support open architectures. This will allow the Navy to field a rapid, adaptable warfighting network, easily tailored to the task at hand which will increase combat effectiveness. Implementation of this capability is limited by the network resources—specifically radio frequency (RF) communications bandwidth—which the Navy has at its disposal (PEO C4I, 2011). This means some network applications must take priority over others.

To understand the needs of the warfighter, this study looks at the centerpiece of U.S. naval strategy, the carrier strike group (CSG). Naval carriers are dynamic platforms equipped with a wide variety of systems which may be used for both combat and non-combat missions. The carrier is escorted by vessels equipped with sensors and weapons

designed for battle at sea, each of them manned by technically proficient crews capable of not only naval combat but also disaster and humanitarian relief. Given the ability to reach distant locations in a timely manner and its operational flexibility, the CSG often provides the first American response to natural disasters both in the U.S. and abroad. As the central instrument of war and peace for the Navy, the CSG is an ideal place to start thinking about a prioritization scheme focused on the warfighter.

The Navy manages network Quality of Service (QoS) using the Automated Digital Network System (ADNS). The current network prioritization scheme implemented on ADNS is designed to optimize network performance based on application characteristics and does not rank applications based on their use by the warfighter in a combat environment. While this approach may work for a bandwidth-rich environment typically found in the civilian sector, it does not fully support the main purpose of Navy tactical networks, that is, warfighting.

In this study, we use the Capability-Based Competency Assessment (CBCA) suggested by Suttie and Potter (2008) to link CSG air detect-to-engage mission essential task lists (METLs) to the personnel and systems required to complete them. These competencies act as operational nodes on which the high-level architecture is developed using the Department of Defense Architectural Framework (DoDAF) Version 1.5 products to capture the roles and responsibilities of each of the individuals who make up a ship's air defense team.

The resulting prioritization scheme aligns operational nodes and services within the overall system architecture so that commanders are able to more effectively use existing network resources to accomplish required tasks within a compressed time frame. By linking the identified systems to the application types ADNS recognizes, we provide mission-specific justification for the prioritization of one network application over another. Finally, we develop a simulation model that captures the current Navy data processing environment. The model is used to compare our prioritization scheme to current network prioritization templates in the context of an air detect-to-engage scenario.

This study illustrates the use of an architectural model to align warfare commander's priority and intent with existing network capabilities and provides a common tool for communicating warfare commander's intent to those responsible for carrying out that intent. This approach should be used to help Navy networks achieve the warfighting capacity for which they were designed.

Current Bandwidth Allocation Scheme

Given the different roles and missions that the CSG is expected to support, flexibility in communications priorities is important. As air operations move from providing defense capability to enabling the movement of supplies and evacuation of the wounded, network priorities must be able to shift. This idea extends logically to varying tactical missions as well. The priorities during air defense operations are not the same as those during an anti-submarine scenario or even normal underway steaming. Clearly, the overall effectiveness of the CSG will be maximized by giving priority to mission-critical applications, which change as the mission changes.

The idea of mission-based network prioritization has not been lost on the fleet at large. There is an increased demand for the ability to modify QoS priorities, based on mission-specific tasking (Rambo, 2011). The goal is to reduce network response times and increase network throughput of the mission-critical information, thus providing more time for the commander to make the "right" choices, leading to increased mission effectiveness and less wasted network resources.

The Navy currently uses the Automated Digital Network System (ADNS) to allocate bandwidth at sea. Initially fielded in the late 1990s, ADNS works by routing outbound data from the ship through the various radio frequency (RF) paths available for its transmission. One of the important capabilities of ADNS is the delivery of basic QoS capability. QoS enables the network to make "smart" decisions when available network resources are overtaxed by the amount of information they are being required to route (Rambo, 2011).

ADNS has evolved over the years to improve bandwidth management and enhance QoS administration; however, there is still room for improvement. The current ADNS version, Increment Three (ADNS INC III), enables QoS through static application prioritization. ADNS works to mark data packets generated by these applications and then transmits them through a "packetshaper" that assigns a priority to the traffic being transmitted. These packets are then sorted into bins according to their assigned prioritization and transmitted accordingly. The prioritization scheme is determined by the Naval Cyber Forces (NCF) command and can only be modified through an extended process which is not subject to change by ship's force (Rambo, 2011).

Shipboard networks are divided into Top Secret/Sensitive Compartmentalized Information (TS/SCI), Secret, Unclassified, and separate Coalition classification enclaves. There is an additional enclave dedicated to network overhead and encryption. A "type of service" header is assigned within each classification enclave to route data packets generated by shipboard applications to various network queues. Each queue is allocated a minimum amount of bandwidth.

Once data packets have been routed to their appropriate queues, transmission is dictated by either First In First Out (FIFO)—that is, the first data packet to arrive is the first to leave—or by Cisco Weighted Random Early Detection (WRED). WRED works by having the network router (ADNS in this case) randomly drop IP packets being sent by applications. The dropping of packets signals that the network is congested, causing the applications that are generating the packets to slow down the rate of transmission. Although the dropping of packets is random, the probability of a drop is not. Applications assigned a higher priority have a lower probability of drop and thus, a higher throughput. Additionally, if applications are not utilizing the minimum bandwidth allowed, that bandwidth is shared with other applications.

The prioritization in ADNS is done via a formal submission process and the application priority is validated by Naval Cyber Forces (Rambo, 2011). Given the changing priorities of separate mission areas, it is imperative that shipboard personnel be able to assign prioritizations dynamically to shipboard network services. This need continues to grow as the Navy's Consolidated Afloat Networks and Enterprise Services (CANES) system is fielded.

CANES will serve to consolidate and replace five existing legacy networks afloat. These systems include the Integrated Shipboard Network System (ISNS), Sensitive Compartmented Information (SCI) Networks, and Combined Enterprise Regional Information Exchange System Maritime (CENTRIXS-M). Using the Service-Oriented Architecture (SOA)[1] concept, CANES will eliminate redundant legacy hardware and replace them with a single, consolidated system. According to the CNO's CANES Initial Implementation and Action Message, DTG 071927Z DEC 09, all shipboard systems that will be fielded after the implementation of CANES must be compatible with the new common network hardware.

[1] Lund et al. (2007) defined Service-Oriented Architecture (SOA) in the military context as "a way of making military resources available as services so they can be discovered and used by other entities that need not be aware of those services in advance."

This single, common computing environment will provide the necessary framework to implement QoS at a higher level of granularity.

The Capabilities-Based Competency Approach

The Capabilities-based Competency Assessment (CBCA) was developed at the Naval War College for manpower analysis. It seeks to identify functional roles working within a team construct versus looking at billets and shipboard occupations. Functional roles are linked to “subtasks” which together define the complete mission-level tasking. The major distinction of CBCA is the focus on capability versus a set of competencies (Suttie & Potter, 2008). Once the *capability* inherent to the role is understood, its relationship to other roles working in the total system can be comprehended.

Unlike the traditional, billet-based allocation of personnel, CBCA links METLs to the personnel and systems required to complete them. It defines “roles” which act as critical nodes that correspond to a DoDAF Operational Node Connectivity Description (OV-2; Suttie, 2011) of the overall operational architecture. These roles are capability based and independent of the personnel assigned to complete them.

This study uses the CBCA approach by first identifying METLs related to a CSG air detect-to-engage scenario. The METLs are then used to describe a set of competencies including operations, personnel, and system requirements inherent to air defense operations. The Service-Oriented Architecture framework is formed by assigning METLs to the operational nodes responsible for their execution. These relationships can be captured in a DoDAF Operational Activity Model Description (OV-5). This model is completed in conjunction with a DoDAF Systems Functionality Description (SV-4), which not only captures the decomposition of the top-level activity, but also identifies the systems used to enable functionality. Finally, the relationships between the operators, their responsible actions, and the systems used to complete those actions are captured via a DoDAF Operational Activity to Systems Function Traceability Matrix (SV-5a). By doing so, the relationships between the operational nodes and the systems that each node uses to accomplish those tasks are identified.

These products are used to understand the relationships between operator and machine and allow the warfare commanders to assign the correct prioritization to the systems at their disposal. Once form has been matched to function, it is possible to understand which nodes and, as a result, which systems are needed to complete an aggregate task. This process provides justification and realization of the most beneficial arrangement for network prioritization. By assigning the highest level of prioritization to those network applications needed to accomplish mission-appropriate tasking, a strike group’s network resources are used to their fullest capability. The performance of all other systems that are not crucial to the completion of the assigned tasking should be sacrificed in order to benefit those that are imperative.

Defining the Operational Nodes

Before system prioritization can take place, the users that will operate the system must be identified. For the CSG air detect-to-engage scenario, this is accomplished using a DoDAF OV-2 diagram showing the relationships between a single air-defense unit (ADU) and the off-ship warfare commanders and coordinators (see Horton, 2012, p. 23). The next step is to identify the tasks associated with each user related to air defense operations. These tasks can be found in the Navy’s Universal Naval Task List (UNTL) discussed in the next paragraph.

The UNTL describes tasks that can be completed by naval forces. The UNTL is used by commanders to determine what tasks can be accomplished by the naval elements under their commands. METLs are derived from this list and are used to support a commander's assigned mission. They serve as a command's list of tasks that are considered essential for mission accomplishment (Chief of Naval Operations, Commandant, U.S. Marine Corp, Commandant, U.S. Coast Guard, 2007). The UNTL is subdivided into separate task levels for each level of warfare. The prefix for tactical level tasks is TA, thus naval tasks at the tactical level are known as Navy Tactical Tasks (NTA). An examination of the UNTL reveals which NTA's are relevant to air defense. By using the descriptions provided in the UNTL for each NTA, it is possible to compile a list of those tasks which are related to air defense (see Horton, 2012, p. 34).

A DoDAF OV-5 describes the operations required to complete a mission and shows the flow between operational activities. The model is constructed by taking each of the NTAs identified as relevant to air defense operations, establishing a hierarchy of those tasks, and mapping each NTA to the operational node responsible for its completion (see Horton, 2012, p. 36).

Having identified the operational activities involved in the process of conducting air defense and linking each of these activities to the operational node responsible for their completion, the next step is to identify the information systems that each of those operational nodes require to complete their assigned tasking. Linking the form to function will provide the justification for our prioritization scheme.

Identifying Systems Required for Air Defense Operations

The Command, Control, Communications, Computers, and Intelligence (C4I) Masterplan serves to summarize the major attributes of DoN network-centric systems. The Masterplan provides C4I system baselines for each type of ship, including carriers and ships assigned to the CSG. These baseline descriptions may be used to identify systems which communicate via ADNS. By using the system descriptions presented in the C4I Masterplan, a list was developed of those systems required to conduct air defense operations (Table 1).

It should be noted that while the systems chosen provide a good representative sample of those systems which may be used in air-defense operations, this list should by no means be considered exhaustive. The C4I Masterplan provides only system overviews and does not give detailed explanations of each system and its capabilities. In order to correctly identify each relevant system, subject matter experts on each would need to be consulted, and personnel familiar with the entire C4I portfolio would need to compile an exhaustive list. For purposes of this study, however, it is sufficient to include these systems to illustrate our approach.

Table 1. Air Defense Net-Centric Systems
(adapted from PEO C4I, 2011)

System Name	Description	Ship Type
Ship's Signal Exploitation Equipment (SSEE) Increment E/F	Provides: 1) Direction finding (DF) 2) Signal acquisition 3) Hostile Forces Integrated Targeting Service (HITS) 4) Digital Receiver Technology (DRT) geolocation capability 5) Integrated signal analysis and select National Security Agency (NSA) applications via the Cryptologic Unified Build (CUB) toolbox	CVN, CG, DDG
AN/USQ-172(V)10 Global Command and Control System–Maritime (GCCS–M)	Provides: 1) Unit location and amplifying information 2) Fuses, correlates, filters, maintains, and displays location and attribute information on friendly, hostile, and neutral land, sea, and air forces, integrated with available intelligence and environmental information to develop Common Operational Picture (COP) 3) Aides decision-maker	CVN, CG, DDG
Distributed Common Ground System–Navy (DCGS–N)	Provides: 1) Integrates shared intelligence data, information, and services between various intelligence and decision-making entities 2) Distributable intelligence products	CVN
Naval Integrated Tactical Environment System, Variant IV (NITES–IV)	Provides: 1) Operational and tactical METOC support to Navy, Marine Corps, and Joint Forces engaged in worldwide operations, ashore and afloat 2) Distributes gathered meteorological data	CVN

Using these systems, we can capture the capabilities each one provides. This is accomplished using a System Functionality Description. The DoD (2007) guidance in *Architecture Framework, Version 1.5, Volume II*, defines a System Functionality Description (SV-4a) as documenting system functional hierarchies and system functions and how data flows between them. A System Functionality Description for air defense is constructed by taking each of the systems identified as relevant to air defense operations and breaking them down to their required functionality. The relationships between those systems are then mapped, providing the structure of the viewpoint (see Figure 1).

Having now identified the functionality that each air-defense unit provides, we are ready to link the system function to the operational tasks we previously identified. This is accomplished using a Systems Functional Traceability Matrix, as described in the next section.

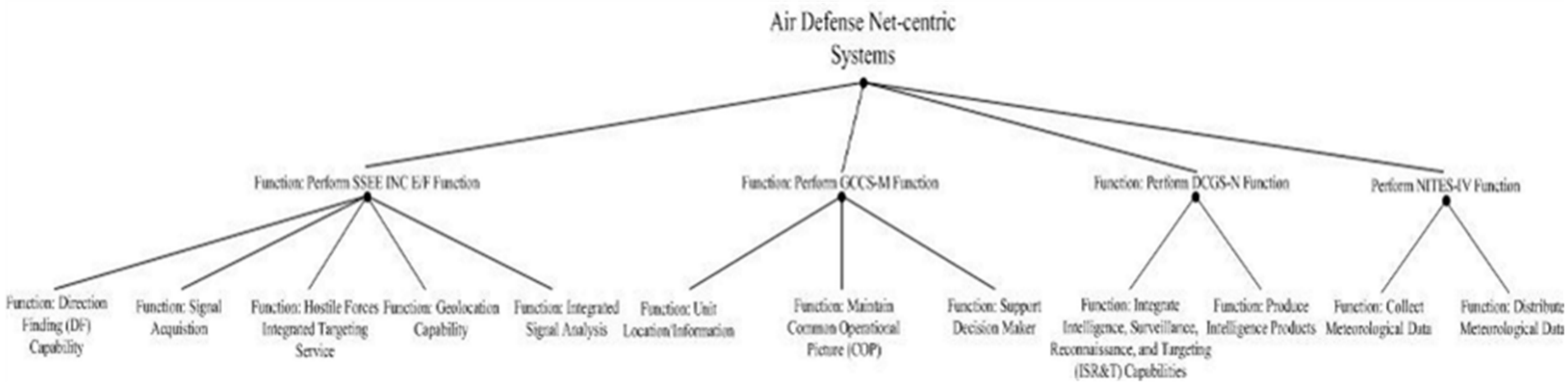

Figure 1. Conduct Air Defense (DoDAF SV-4a) System Functionality Description

Linking Operational Activities to Systems Functions

A Systems Functional Traceability Matrix (DoDAF SV-5a) documents the relationship between the operational activities and system functionality present in the overall architecture (see Table 2). Those systems which are being used by an operator to complete a task are indicated with an X in Table 2. For now, only those systems that connect to the Global Information Grid (GIG) via an Internet Protocol (IP) pipeline have been mapped. As new systems are fielded to be deployed on CANES, this diagram would need to grow to include them. The dashed area indicates that those systems are not currently available for those users.

By identifying the systems used by operators to complete assigned tasks, it is possible to identify the systems most useful to a mission, in this case, air operations. These are the systems which should be given priority in an air detect-to-engage scenario. This methodology can be applied to any given mission or tasking.

Each information system has now been linked to the task associated with its use, and each task has been linked to the operator who completes that task. Our proposed prioritization scheme will place each of the identified systems at the top of the priority scheme. A comparison of the current priority scheme and our proposal will be outlined in the next section.

Table 2. Conduct Air Defense SV-5a, Systems Function Traceability Matrix

SYSTEM FUNCTIONS												OPERATIONAL ACTIVITIES	
NITES - IV		DCGS-N		GCCS-M			SSEE INC E/F						
2) Distribute Meteorological Data	1) Collect Meteorological Data	2) Produce Intelligence Products	1) Integrate Intelligence, Surveillance, Reconnaissance, and Targeting Capabilities	3) Support Decision Maker	2) Maintain Common Operational Picture	1) Unit Location Information	5) Integrated Signal Analysis	4) Geolocation Capability	3) Netcentric Forces Integrated Targeting Service	2) Signal Acquisition	1) Direction Finding (DF) Capability		
				X	X	X						NTA 5 - Exercise Command and Control	SW
X	X	X	X				X	X	X	X	X	NTA 5.1 - Acquire, Process, Communicate Information and Status	SW
		X	X	X	X	X						NTA 5.2 - Analyze and Assess Situation	SW
				X	X	X						NTA 5.4 - Direct, Lead, and Coordinate Forces	SW
												NTA 6 - Protect the Force	SW
												NTA 6.1 - Enhance Survivability	SW
												NTA 6.1.1 - Protect Against Combat Area Hazards	SW
												NTA 6.5 - Perform Consequence Management	SW
X	X	X	X	X	X	X	X	X	X	X	X	NTA 2 - Develop Intelligence	BQ
		X	X									NTA 2.1 - Plan and Direct Intelligence Operations	BQ
		X	X				X	X	X	X	X	NTA 2.2 - Perform Collection Operations and Management	BQ
		X	X									NTA 2.3 - Process and Exploit Collected Information and Intelligence	BQ
X	X	X	X	X	X	X						NTA 2.4 - Conduct Analysis and Produce Intelligence	BQ
		X	X	X	X	X						NTA 2.5 - Disseminate and Integrate Intelligence	BQ
		X	X									NTA 2.6 - Evaluate Intelligence Operations	BQ
							X	X	X	X	X	NTA 5.5 - Conduct Information Warfare (IW)	BQ
				X	X	X						NTA 6.1.1.3 - Positively Identify Friendly Forces	FOTC
												NTA 3 - Employ Firepower	CO
												NTA 6.5.2 - Coordinate Damage Control Operations	CO
				X	X	X						NTA 3.1 - Process Targets	TAO
												NTA 3.2 - Attack Targets	TAO
												NTA 2.2.1 - Collect Target Information	AAWC
												NTA 3.2.7 - Intercept, Engage, and Neutralize Enemy Aircraft and Missile Targets (Defensive Counter Air)	AAWC
							X	X	X	X	X	NTA 2.2.3 - Perform Tactical Reconnaissance and Surveillance	EW
												NTA 3.2.5 - Conduct Electronic Attack	EW
							X	X	X	X	X	NTA 5.5.4 - Conduct Electronic Warfare Support (ES)	EW
												NTA 3.1.5 - Conduct Tactical Combat Assessment	RSC

Quality of Service Model

Quality of Service (QoS) management for shipboard IP networks is implemented by marking IP packets using the "type of service" (ToS) header field. The Automated Digital Network System (ADNS) uses the first six bits within the header to mark each packet with a Differentiated Services Code Point (DSCP; Automated Digital Network System, 2011). These DSCP markings can be used to separate network traffic into class bins which can be used to implement separate controls in off-ship transmission. The routing of packets is done without regard for the security level classification.

To test the effectiveness of a prioritization scheme in the current Navy environment, we need to model the DSCP process used by ADNS. A stochastic simulation was developed using the *ExtendSim 8* software to model this process. Figure 2 shows the basic outline of the model that will be used to aid discussion of QoS implementation within ADNS. It is important to note that our simulation focuses on how prioritization schemes impact data throughput and latency within the context of the air detect-to-engage scenario. We are not modeling the events that might occur in the scenario, but rather using the scenario to understand the expected information requirements and data traffic within each phase of an air detect-to-engage (DTE) scenario.

ADNS separates network traffic into five separate Community of Interest (COI) local area networks (LANs). They are SECRET, TS-SCI, UNCLASS, CENTRIXS (coalition), and an additional classification for Cipher Text Core Traffic (Automated Digital Network System, 2011) and are shown on the left side of Figure 2. Each LAN is comprised of various IP-based network applications which are classified according to queuing doctrine, such as First-In, First-Out (FIFO) or Class-Based Weighted Fair Queuing (CBWFQ). These applications are listed within the *Traffic Classes, Packet Marking, and Priority Processing* documentation provided by the Program Manager, Warfare (PMW) 160 Office.

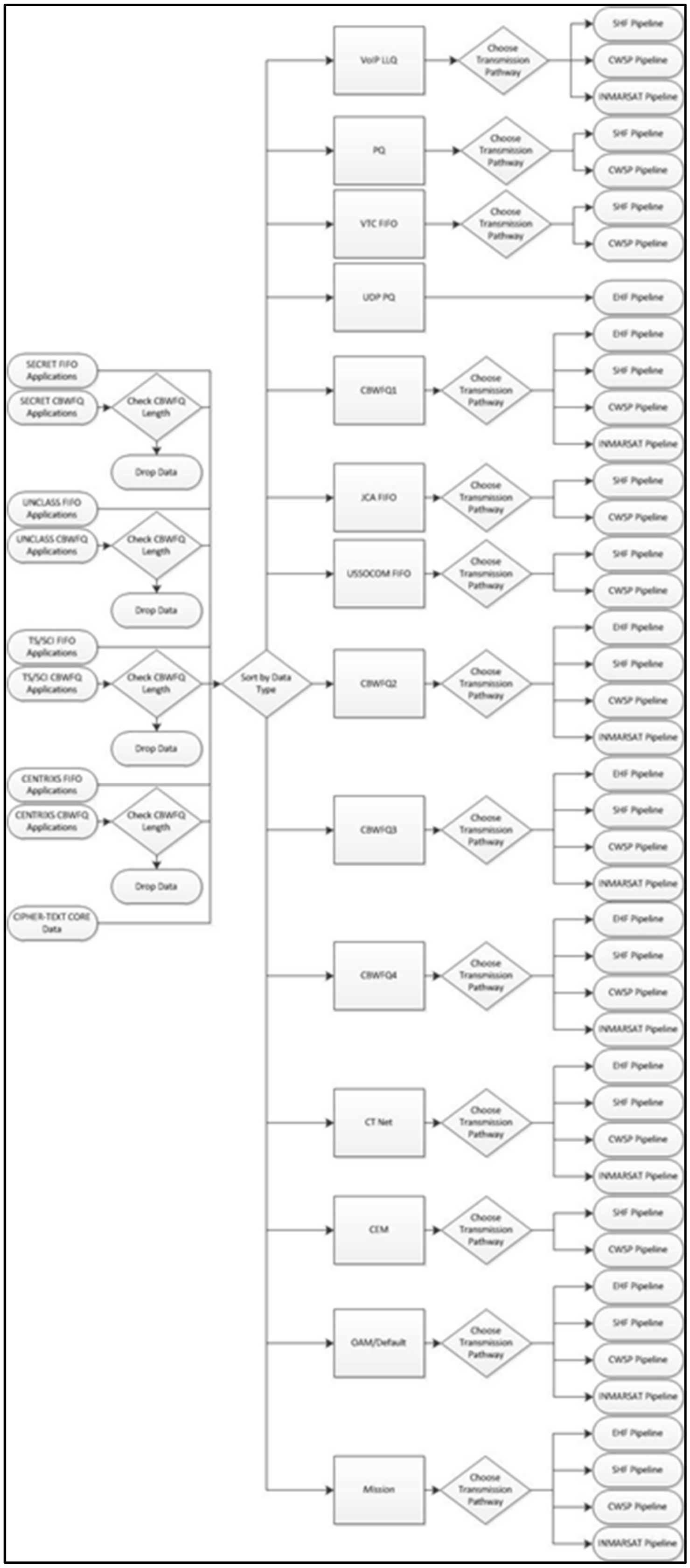

Figure 2. Flow Diagram Representation of ExtendSim 8 Model

Each of the applications which comprise the COI LANs is represented in our model by a block that creates "packets" at a random interval. Mean inter-arrival time for each type of application varies depending on the type of service it performs, as shown in Table 3.

Table 3. Application Type Inter-Arrival Parameters

Application Type		Mean Inter-Arrival Period	Standard Deviation
Video		33 ms	1 ms
VoIP		100 ms	10 ms
Data		200 ms	20 ms
Network Overhead		50 ms	1 ms

The inter-arrival periods were modeled using a normal distribution, bounded by zero on the left side, with a standard deviation, as indicated in Table 3. Although network traffic behavior is usually "bursty" and the inter-arrival times are not typically normally distributed, we chose the normal distribution for simplicity. In addition, we use a "worst case" scenario in which every application is creating the maximum amount of data possible, with 1,500 bytes per packet. While the two simplifying assumptions introduced in our model would most likely not occur in real-life, they facilitate comparison of prioritization schemes and limit the number of independent variables in the model.

Each of the packets generated in the simulation was marked with a priority based upon the type of information it is carrying. This marking allows for the packet to be routed to one of the fourteen separate queues, as shown in Figure 2. ADNS currently specifies 13 different queue types, based upon network application behavior (Automated Digital Network System, 2011). We introduce a 14th *Mission Queue* which is reserved for those applications deemed most relevant to air defense operations based on our previous analysis. This is the simplest way to test our proposed prioritization scheme against the existing ADNS scheme. Actual implementation of the prioritization scheme by the Navy might differ based on network configuration and other considerations.

The model is designed to incorporate only those bandwidth pipelines available to a particular class of ship. Thus, CVNs will be allowed the CWSP, SHF, and EHF pipelines, and DDGs and CGs will be allowed the SHF, EHF, and INMARSAT pipelines. The model works to balance the load between each of the transmission pipelines available to each queue type shown in Figure 2.

The model checks each time step to see which queues require bandwidth and which do not. It will first subtract that amount of bandwidth that has been assigned to the queues that currently require it from the total amount of bandwidth available. Then it will parse out the remaining bandwidth following the same percentage assignment schedule as outlined in the *Traffic Classes, Packet Marking, and Priority Processing* documentation provided by the PMW 160 Office.

ADNS uses two methods for the queuing doctrine applied to each queue. First, applications which are weighted equally within the same queue are handled by a FIFO methodology. Second, applications which are weighted differently, though routed to the same queue, are handled using CBWFQ with Weighted Random Early Detection (WRED). CBWFQ will route those packets with a higher priority at the expense of those with a lower priority. This is accomplished by randomly dropping lower priority packets once a queue has reached a pre-determined length. In our model, we sample the current queue length for

each time step. If the sampled queue length falls within the set boundaries, packets are dropped according to scheduled packet drop probability.

Within ADNS, random dropping denies the originating application a receipt acknowledgment and forces the application to retransmit the packet. Eventually, this causes the originating application to slow down its transmission rate, allowing higher priority applications to transmit at a faster rate (Automated Digital Network System, 2011). In our model, this metric is captured by measuring the amount of packets that actually were transmitted and comparing that value to the amount of packets that were created. This gives a percentage of actual throughput and will be used as a measure to compare the effectiveness of a given priority scheme as it applies to mission-specific applications.

Results and Conclusion

The simulation model was designed to measure latency and throughput. Latency refers to the timeliness of data. By recording latency, we gain an understanding of how long it takes for data to be created, routed, and then transmitted. Throughput refers to how much of the data created is actually transmitted in the time allowed. Throughput is an indicator of the quality of the transmission.

The air detect-to-engage scenario consists of three stages—surveillance, escalation, and terminal. During the surveillance phase, there is no threat and normal air defense operations are in effect. The surveillance phase provided baseline measurements of latency and throughput using current ADNS settings. Average percent throughput and latency for both the carrier (CVN) and the cruiser/destroyer (CRUDES) escorts over a total of 30 runs were recorded.

Next we modeled the escalation phase. During this phase, the strike group receives indications of a pending attack on the high value unit (HVU). In response, the strike group commander will probably increase the threat warning posture which brings the force to a higher state of readiness in preparation for a possible attack via the air. To support this condition, we propose the prioritization scheme shown in Table 4 because it prioritizes the systems designed to aid anti-air warfare.

The bandwidth percentages assigned to each queue are intended to minimize latency and maximize throughput of systems relevant to air defense, while minimizing the impact to other systems. It should be noted that these percentages are notional, but should be selected so that they support the information needs of the commander.

Table 4. CBCA Bandwidth Allocation Scheme—Escalation Phase

Escalation Phase				
	CWSP	SHF	EHF	INMARSAT
Group 1	33%	19%	N/A	N/A
CEM	15%	25%	N/A	N/A
VTC	12%	12%	N/A	N/A
JCA	18%	12%	N/A	N/A
SECRET (CBWFQ1)	12%	7%	27%	17%
UNCLAS (CBWFQ2)	6%	4%	12%	7%
CENTRIXS (CBWFQ3)	6%	4%	12%	4%
SCI (CBWFQ4)	13%	5%	17%	14%
Other				
VoIP (LLQ)	384 kbps	384 kbps	N/A	57 kbps
PQ (FMV)	10%	10%	N/A	N/A
UDP	N/A	N/A	10%	N/A
USSOCOM	24%	24%	N/A	N/A
CTNet (CONTROL)	1%	1%	2%	2%
OAM/Default	11%	25%	5%	41%
Mission	21%	21%	15%	15%

Table 4 shows the queues currently utilized with the ADNS (Automated Digital Network System, 2011) as well as a Mission queue that implements our prioritization scheme. The four columns presented in Table 6 represent the four transmission paths available to the strike group ships: Commercial Wideband Satellite Program (CWSP)—CVN only, Super High Frequency (SHF), Extremely High Frequency (EHF), and International Maritime Satellite (INMARSAT)—CRUDES only (Automated Digital Network System, 2011). The values in each block represent the percentage of bandwidth available on each transmission path, that is, column, applied to each queue, that is, row, with the exception of Voice over Internet Protocol (VoIP), which is a flat amount.

In the escalation phase, we assume that the traffic output of systems relevant to air defense would increase due to the now-present threat and the information being gathered about it. For modeling purposes, we doubled the data output in this phase. The average latency (milliseconds) and throughput (percentage) over 30 runs was recorded and compared with latency and throughput for each data type for each prioritization scheme.

The third phase of evaluation is the terminal phase. During this phase, the inbound threat has fired its weapon at the HVU, prompting the commander to further escalate the strike group's readiness posture. To support this condition of readiness, we propose the prioritization scheme shown in Table 5. The bandwidth percentages selected for this phase reflect an increased amount of air-defense relevant network traffic. Again, percentages are notional. Actual percentages would be based on the commander's priority and intent.

Table 5. CBCA Bandwidth Allocation Scheme—Terminal Phase

Terminal Phase				
	CWSP	SHF	EHF	INMARSAT
Group 1	30%	15%	N/A	N/A
CEM	15%	25%	N/A	N/A
VTC	12%	12%	N/A	N/A
JCA	18%	12%	N/A	N/A
SECRET (CBWFQ1)	12%	7%	25%	15%
UNCLAS (CBWFQ2)	6%	4%	11%	7%
CENTRIXS (CBWFQ3)	6%	4%	10%	4%
SCI (CBWFQ4)	13%	5%	15%	13%
Other				
VoIP (LLQ)	384 kbps	384 kbps	N/A	57 kbps
PQ (FMV)	10%	10%	N/A	N/A
UDP	N/A	N/A	10%	N/A
USSOCOM	22%	22%	N/A	N/A
CT Net (CONTROL)	1%	1%	2%	2%
OAM/Default	10%	25%	5%	37%
Mission	27%	27%	22%	22%

The data output of the air defense applications was again effectively doubled—now four times the initial value, assuming that the traffic output of those applications would increase significantly during the terminal phase.

Independent two-sample, single-tailed Student t-tests were conducted to determine whether there is a statistically significant difference between the baseline latency and throughput and the latency and throughput using our prioritization scheme. The results are shown in Tables 6–9.

Table 6. CARRIER Latency Hypothesis Test Results

CARRIER LATENCY HYPOTHESIS TEST						
APPLICATION NAME	PHASE	H_o	H_a	t_{obsv}	t_{crit}	Reject H_o
High Priority Applications	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	153.023	1.672	Yes
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	95.038	1.672	Yes
GCCS-M, NETPREC	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	84.214	1.672	Yes
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	123.864	1.672	Yes
Time Sync, Chat, Cop, HFDF	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	162.315	1.672	Yes
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	30.383	1.672	Yes
Email, CERCIS, OS/BD, PARA126,	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	128.046	1.672	Yes
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	29.111	1.672	Yes
Name Resolution, Encryption, File	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	190.009	1.672	Yes
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	27.310	1.672	Yes
EVCP, Big Brother, ISRT	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	210.461	1.672	Yes
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	26.628	1.672	Yes

Table 7. CRUDES Latency Hypothesis Test Results

CRUDES LATENCY HYPOTHESIS TEST						
APPLICATION NAME	PHASE	H_o	H_a	t_{obsv}	t_{crit}	Reject H_o
High Priority Applications	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	101.763	1.672	Yes
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	56.621	1.672	Yes
GCCS-M, NETPREC	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	99.548	1.672	Yes
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	53.294	1.672	Yes
Time Sync, Chat, Cop, HFDF	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	173.293	1.672	Yes
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	55.064	1.672	Yes
Email, CERCIS, OS/BD, PARA126,	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	174.240	1.672	Yes
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	57.352	1.672	Yes
Name Resolution, Encryption, File	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	157.239	1.672	Yes
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	60.639	1.672	Yes
EVCP, Big Brother, ISRT	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	161.854	1.672	Yes
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 > \bar{X}_2$	51.898	1.672	Yes

Table 8. CARRIER Throughput Hypothesis Test Results

CARRIER THROUGHPUT HYPOTHESIS TEST						
APPLICATION NAME	PHASE	H_o	H_a	t_{obsv}	t_{crit}	Reject H_o
High Priority Applications	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	1.015	-1.672	No
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-1.172	-1.672	No
GCCS-M, NETPREC	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	0.448	-1.672	No
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-0.685	-1.672	No
Time Sync, Chat, Cop, HFDF	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-3.247	-1.672	Yes
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-21.000	-1.672	Yes
Email, CERCIS, OS/BD, PARA126,	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-1.206	-1.672	No
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-22.156	-1.672	Yes
Name Resolution, Encryption, File	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-3.808	-1.672	Yes
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-21.693	-1.672	Yes
EVCP, Big Brother, ISRT	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-2.424	-1.672	Yes
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-22.553	-1.672	Yes

Table 9. CRUDES Throughput Hypothesis Test Results

CRUDES THROUGHPUT HYPOTHESIS TEST						
APPLICATION NAME	PHASE	H_o	H_a	t_{obsv}	t_{crit}	Reject H_o
High Priority Applications	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	8.063	-1.672	No
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-1.514	-1.672	No
GCCS-M, NETPREC	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-9.655	-1.672	Yes
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-1.472	-1.672	No
Time Sync, Chat, Cop, HFDF	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-427.218	-1.672	Yes
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-158.074	-1.672	Yes
Email, CERCIS, OS/BD, PARA126,	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-445.372	-1.672	Yes
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-158.543	-1.672	Yes
Name Resolution, Encryption, File	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-387.054	-1.672	Yes
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-169.129	-1.672	Yes
EVCP, Big Brother, ISRT	Escalation	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-373.809	-1.672	Yes
	Terminal	$\bar{X}_1 = \bar{X}_2$	$\bar{X}_1 < \bar{X}_2$	-160.739	-1.672	Yes

We note that there is a statistically significant decrease in the average latency associated with each of the selected applications using our prioritization scheme as compared to default ADNS settings. Our results also indicate statistically significant increases in throughput using our prioritization scheme for most applications; however, there is no significant difference for some applications. We note decreases in percent throughput for the *High Priority Applications* data types for both the CARRIER- and CRUDES-type ships during the Escalation Phase as well as GCCS-M, NETPREC data types for the CARRIER during the Escalation Phase when using our prioritization scheme. This decrease in percent throughput is offset by marked decreases in associated latency which should be taken into consideration when implementing our process for network prioritization.

An important question is whether the differences noted in Tables 6–9 are practically significant. One of the primary reasons for the selection of the air detect-to-engage scenario is that time is often at a premium. For example, consider the time savings for the CRUDES class ships during the terminal phase of engagement. Our prioritization scheme saves on average, approximately 9s in time delays for our selected applications as compared to the default ADNS prioritization scheme. In order to understand the importance of this time savings, we use the cruising speed of a typical hostile missile, the C-801 (595 knots). Using the formulas for time distance, we see the actual distance the missile may travel in this allotted time is almost one and a half nautical miles.

$$\begin{aligned} d &= vt \\ d &= (0.165nmi/s)(9s) \approx 1.486nmi \end{aligned} \tag{1}$$

So ultimately, what does the time/distance savings buy us? As the Navy becomes more and more net-centric, more shipboard systems will be used in the identification and prosecution of hostile targets. Every millisecond we save in the transmission of data results in increased ranges at which we may engage hostile targets. This means more time for human decision-makers to draw conclusions and more opportunities for us to put ordnance on target. In their book, *Human Factors in Simple and Complex Systems*, Proctor and Van Zandt (2008) defined a reaction-time task as that which requires a person to respond to a stimulus as quickly as possible. They highlighted recent work conducted in continuous information accumulation. They noted that the fastest possible human reaction to visual stimuli is 150 ms. This reaction time slows linearly, following a log2 scale, with the number of possible stimuli and responses available to the operator.

If we assume the previously described mean reaction time, we see that the time savings described in this paper are within the threshold of human reaction. This is critical as it allows for an actual physical response by a human operator. The more the latency of our selected data is reduced, the more time the human decision-maker has to react to the visual stimulus. This impact is even more pronounced if we consider the near instantaneous reaction time of automated systems. Given an autonomous response capability, milliseconds saved in transmission time can directly translate to whether an enemy target may be destroyed in the allotted time or if it will strike its intended target.

We have demonstrated a process that seeks to align system prioritization with operator needs based upon mission tasking. We accomplish this by linking operational tasking to warfighters and identifying those systems used by the warfighters to accomplish said tasking. Our work may be seen as a guideline for the development of network prioritization schemes which seek to optimize Navy networks for combat and are in keeping with the philosophy of net-centric warfare (NCW). Ideally, this approach will help strike group commanders see their networks as true weapon systems and help bring to the forefront those network systems relevant to the mission-at-hand.

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The Impact of Computer-Based Training on Operating and Support Costs for the AN/SQQ-89(v) Sonar System

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Abstract

The U.S. Navy transitioned to computer-based training (CBT) in A and C schools in 2003 after a 2001 *Revolution in Training* report claimed that the Navy would realize savings in cost and training time without negatively affecting the quality of sailors arriving to the fleet. Anecdotal evidence from ship personnel suggested otherwise. This study analyzes maintenance data for the AN/SQQ-89(v) sonar system to determine whether the transition to CBT contributed to increased fleet maintenance costs.

Government studies showed that the conversion to CBT was not the sole contributing factor to increased fleet maintenance costs or degraded fleet material readiness. Changes to the Navy's training, maintenance, and manning programs during the early 2000s were all contributing factors. If the conversion to CBT were to have an effect anywhere in the Navy maintenance system, it should be seen in maintenance activities where sailors were performing maintenance on ships. Our analysis revealed that the average cost of these activities was significantly greater after CBT was implemented. This would support the anecdotal evidence that CBT was impacting the quality of maintenance on ships.

Introduction

Traditionally, the majority of specialized skills training (known as "A" and "C" schools) in the Navy has taken place in a classroom setting with instructors. At the turn of the century, Navy leadership became concerned that current training programs would not adequately meet future demands. As a result, the chief of naval operations (CNO) chartered an Executive Review of Navy Training (ERNT) to review the Navy training system and recommend solutions to improve training effectiveness and meet future training demands.

The ERNT group noted that formal schoolhouse training requires a large investment in facilities, instructors, and laboratories and that future training demand would outstrip the number of billets available under the legacy schoolhouse system (Executive Review of Navy Training [ERNT], 2001). They suggested that the use of new training technologies could help meet that demand while reducing the cost of training. Motivated by these findings, the Navy established Task Force EXCEL (Excellence through Commitment to Education and Learning) to develop a continuum of lifelong learning, use a streamlined funding process and a single training authority, create a Human Performance Systems Model (HPSM), and link training and acquisition (Naval Personnel Development Command, 2002).

Part of the Navy's new strategy included the use of new training technologies such as distributed learning, computer-based training (CBT), collaborative learning, and computer-mediated learning. The Navy claimed that the introduction of CBT would reduce both training time and training costs without reducing the quality of training received (ERNT, 2001). Accordingly, CBT was introduced full-time into the training pipeline in fiscal year (FY) 2003.

A 2009 Naval Inspector General (IG) Report, *Computer Based Training*, reported that the introduction of CBT did reduce training time. However, sailors arriving to the fleet under CBT did not usually meet the required Knowledge, Skills, Abilities, and Tools (KSATs) upon reporting on board. Because of this, ships had to take the time to train sailors up to acceptable standards (Naval Inspector General, 2009). This suggests that while initial training costs may have been reduced by CBT, the overall cost of operations and maintenance, including on-the-job training (OJT), may have increased.

This study examines the impact of CBT on Navy training costs as well as operations and maintenance costs before and after the implementation of CBT. We first look at Department of the Navy (DoN) Budget Reports from FY2000 through FY2010 to determine the macro-level impact of CBT on Navy costs. At the macro level, there are many variables besides CBT that could contribute to changes in maintenance costs, including the Global War on Terror (GWOT) and increased operations tempo (OPTEMPO). However, it is impractical to isolate the impact of CBT on Navy maintenance costs at the macro level. Instead, it is necessary to look at the impact of CBT on a particular system, program, or technology. This research effort focuses on a single system, the AN/SQQ-89(v) sonar, collecting data at a level of detail that allows for the control of the various variables that might impact maintenance costs.

We start with a discussion of the Navy's classroom training system, the Revolution in Training and CBT, followed by a look at the Navy maintenance process and changes in manning and maintenance policies during the 2000s. Next, we focus on a single Navy system, the AN/SQQ-89(v) sonar system, and examine how the conversion to CBT might have affected maintenance costs in that system.

Training

Training in the Navy occurs throughout a sailor's career. After completing recruit training, sailors are sent to specialized skill training in their designated job specialty, or rating. In-rate training begins in A school, where sailors learn the particular skills specific to their job. From there, a sailor can receive additional training in C school. Once a sailor is assigned to a ship, he or she receives training for collateral duties such as quarterdeck watches, anti-terrorism/force protection watches, weapons handling, and the at-sea fire party. Additionally, sailors can expect to receive general military training in topics ranging from electrical safety to suicide prevention.

Traditional Schoolhouse Training

Until the early 2000s, in-rate training in the Navy was conducted in a formal schoolhouse setting, where instructors delivering the training are subject matter experts (SMEs) on the material they are teaching (ERNT, 2001). Typically, SMEs come from the fleet and have experience working on the equipment they are teaching about. Training is delivered in the form of lectures, and instructors are able to supplement the lecture material with tips and anecdotes from their career experiences (Naval Inspector General, 2009).

In addition to lectures, sailors can reinforce their understanding of the material through hands-on experience in a laboratory setting. In maintenance courses, students are

able to work on the exact equipment they will see in the fleet, and instructors are able to simulate equipment casualties for technicians to troubleshoot. Instructors are able to tailor the delivery of material to a class based on the students' levels of comprehension. For example, if a class has difficulty understanding a particular concept, the instructor can choose to spend more time in the lab to reinforce what is learned during the classroom portion.

There are several benefits to instructor-led training (ILT). Since a single instructor teaches a large group of students, group learning techniques can be employed that would otherwise be unavailable in one-on-one or CBT instruction. The formation of small groups within a class fosters team-building and allows students to help and teach each other. Compared to the costs of software development, testing, and hardware purchase, ILT is in some ways more cost effective, depending on class size and length of use. Additionally, the controlled classroom environment offers fewer distractions than CBT or distance learning. Finally, ILT doesn't take as long to develop as CBT. It takes approximately 34 hours to develop one hour of ILT (Chapman, 2007), while it takes approximately 220 hours to develop a standard e-learning course (Chapman, 2006).

ILT also has its disadvantages. Since everyone has different learning capabilities, some students may be more advanced and become bored while waiting for slower learners to catch up. Conversely, slow learners may have difficulty keeping up. Depending on the size and duration of the course, ILT may be more expensive than CBT.

Revolution in Training

In October 2000, the Executive Review of Navy Training (ERNT) group was charged with providing insights on how to improve and align training organizations, leverage civilian training practices, and use new technologies to provide a continuum of training for sailors. The 24-member group was comprised of military and civilian personnel, members of academia, research institutions, and industry. In 2001, ERNT released their report, *Revolution in Training: Executive Review of Navy Training Final Report.*

During their review, the ERNT group noted that the demands for training had increased. At the macro level, the training demands are driven by the Required Operational Capabilities and Projected Operating Environments (ROC/POE). ROC/POE is a tool that is used to determine specific warfighting missions for each ship. Training requirements are derived from these missions and are then used to determine specific training requirements for sailors.

Changes in the ROC/POE lead to increased ship training requirements which are passed down to the sailor level. The ERNT group noted that the finite number of seats available in the Navy schoolhouses was not able to support the increased training demands. Because of this, there were gaps in the types of training that current and/or potential sailors needed and what could be delivered.

In many cases, this resulted in billets which could not be filled because there were no sailors with the required training to fill them. During the 1990s, several other items contributed to the lack of trained sailors. First, the pool of experienced sailors had decreased due to drawdowns and retirements. Second, it was difficult to compete for trained personnel in a healthy U.S. economy, and many trained sailors were leaving for jobs in the civilian sector.

The ERNT group suggested that technology and the science of learning offered several opportunities to improve the Navy training system by reducing training time through

CBT and offering distributed learning opportunities that could be executed at the workplace. This is discussed further at the end of the report.

Computer-Based Training

Computer-based training, or CBT, is defined as “individual or group self-paced instruction using a computer as the primary training medium, to include web-delivered Navy E-Learning (NEL)” (Naval Inspector General, 2009, p. ii). In Navy A schools, students go through learning modules on a personal computer at their own pace. When students are done processing the information presented on the screen, they click “next” to proceed to the next piece of information. There are usually small knowledge assessments throughout the module, followed by a final knowledge assessment at the end of the module (Naval Inspector General, 2009, p. 7).

Because the learning is self-paced, instructors were replaced with “facilitators.” Facilitators are not necessarily SMEs in the subject matter being delivered in the CBT modules. The purpose of the facilitator is “to ensure classroom rules are followed, assist with computer-related issues, and monitor student progress. They do not provide reinforcement of learning objectives or enhance retention of course material.” The problem with replacing instructors with facilitators is that students cannot go to a facilitator with a question about subject material, removing the opportunity to teach when a student is confused (Naval Inspector General, 2009).

There are several advantages to CBT. The learning is self-paced and if the course is offered as distance learning, the schedule to take the course is flexible. Students can complete the course at their own paces, which generally shortens training time. Since there are no instructors involved, the message doesn’t change from one person to the next (Dhanjal & Calis, 1999). In addition, the Navy was able to reduce training time using CBT, which resulted in cost savings in training manpower and infrastructure, as noted by the Navy IG (2009) and the GAO (2010).

However, the use of CBT raised concerns in the fleet about the level of knowledge of sailors reporting to ships from A schools. The inspector general (IG) noted that sailors arriving to the fleet under CBT did not usually meet the required KSAT standards and were unfamiliar with the equipment they would be working on and the tools they would need to use. Because of this, ships had to take the time to train sailors up to acceptable standards. In fleet interviews, some commands reported that qualification time was nearly double what it was before the introduction of CBT (Naval Inspector General, 2009). The GAO reports in 2010 and 2011 made similar observations and concluded that the change to CBT had a negative impact on readiness.

The Navy IG and GAO reports found that while the Navy’s use of CBT resulted in cost and training time savings, the quality of sailor reporting to the fleet was not as well prepared as ILT-trained sailors of the past. The result is that poorly-trained sailors may have contributed to declining material readiness in the fleet. The next section of this study examines Navy maintenance practices and highlights the findings of the *2010 Fleet Review Panel on Surface Force Readiness* report.

Maintenance

Navy maintenance occurs on three levels: organizational level (O-level), intermediate maintenance (IM) activities, and depot level. This section of the study discusses all three maintenance levels. Additionally, this section discusses changes made to the maintenance process in 2003 which were reported on in the *2010 Fleet Review Panel on Surface Force Readiness* (known as the Balisle Report for its chairman, Vice Admiral [VADM, Retired]

Phillip Balisle), a report that discussed declining fleet readiness as a result of changes to training, maintenance, and manning policies in the early 2000s.

Shipboard maintenance begins with the Planned Maintenance System (PMS). PMS is governed by Naval Sea Systems Command (NAVSEA; 2003) Instruction 4790.8B, *Ship's Maintenance and Material Management (3-M) Manual*. The instruction outlines the requirements for PMS on shipboard systems and equipment. The purpose of PMS is to provide ships with the means to plan, schedule, and perform preventive maintenance onboard and to identify potential equipment problems before the equipment fails.

If corrective maintenance is required, the maintenance is reported, scheduled, and performed through O-level shipboard maintenance. Ship maintenance actions are reported in Navy Visibility and Management of Operating and Support Costs (VAMOSC), under Unit Level Consumption and Manhours—Organizational Corrective Maintenance.

Intermediate maintenance (IM) is "normally performed by Navy personnel onboard tenders, repair ships, Shore Intermediate Maintenance Activities (SIMAs), aircraft carriers, and fleet support bases" (Naval Sea Systems Command, 2003, p. I-5). IM jobs are deferred corrective maintenance jobs that are beyond the capability of the ship's force and are sent off-ship for completion. IM is tracked in Navy VAMOSC under Maintenance—Intermediate.

Depot-level maintenance "requires major overhaul or a complete rebuilding of parts, assemblies, subassemblies, and end items, including the manufacturing of parts, modifications, testing, and reclamation" (Naval Sea Systems Command, 2003, p. I-5). Depot maintenance is reported in Navy VAMOSC under Maintenance and Modernization—Depot, Other Depot.

In 2009, VADM (Ret.) Phillip Balisle was directed to conduct a Fleet Review Panel (FRP) of surface force material readiness. The report noted that 4,052 billets were removed from Navy ships from 2001–2009. While billets were removed from ships, requirements such as maintenance, damage control watches, training, and in-port duties were not reduced (Balisle, 2010). The shortcomings of CBT described in the previous section exacerbated the problems experienced with manning reductions since sailors were not arriving on board with the right KSATs. The result was undermanned ships with poorly trained sailors with not enough time or know-how to perform routine maintenance actions.

In addition to reduced fleet manning, shore facilities also received manning cuts. This means that maintenance that was intended for intermediate maintenance activities was pushed back to ship personnel, which were undermanned and poorly trained. In addition to the shrinking shore workforce, the amount of time the ships were available was shortened from 15 weeks to nine weeks (Balisle, 2010). These actions resulted in equipment being out of commission for longer periods of time.

Finally, the 2010 Balisle report noted that changes in PMS were made because ships couldn't meet maintenance requirements due to reduced manning. Maintenance requirements were either eliminated or extended in periodicity. The intent was to shift maintenance requirements to shore facilities, but since manning was reduced ashore, many requirements went away completely. The elimination and extension of maintenance requirements can lead to more opportunities for equipment to become inoperable, resulting in degraded fleet readiness (Balisle, 2010).

The Navy introduced several major changes to training, maintenance, and manning policies during the early part of the 2000–2010 decade. The Balisle report found that training was a factor, but certainly not the only factor, that led to degraded fleet readiness. Manning reductions would have led to cost savings in the military personnel budget, but the impact of

the reductions may have resulted in maintenance cost increases in future budgets due to deferred maintenance actions, thus confounding the effect of CBT. Similarly, changes in maintenance policies may have impacted maintenance costs in future years. At a macro level, the impact of CBT is impossible to tease out (see Gibson, 2012, for an examination of Navy training, operations, and maintenance budgets between 2000 and 2012). For this reason, we decided to examine one system in particular, the AN/SQQ-89(v) sonar system, in hopes that we could separate the two factors.

AN/SQQ-89(v) Sonar System

To examine the effect of CBT on rising maintenance costs, this study will focus on the operating and support (O&S) costs of a single Navy system, the AN/SQQ-89(v) sonar system, and look at how the conversion to CBT affected maintenance costs in that system. An analysis by Gibson (2012) showed that manning levels for sonar technicians did not change significantly from FY2000–FY2010, effectively eliminating manning as a contributor for the AN/SQQ-89 O&S costs and focusing the study on training and maintenance.

The AN/SQQ-89(v) surface ship Anti-Submarine (ASW) Warfare combat system (referred to as “the 89” in the rest of this paper) is an integrated network of sonar systems designed to search, detect, classify, and engage ASW threats. The system is currently installed on CG-47 class cruisers, DDG-51 class destroyers, and FFG-7 class frigates. The 89 uses a variety of sensors that can transmit (active) and receive (passive) acoustic data in order to detect and classify threats. Data from the sensors can be correlated and targets can be localized using Target Motion Analysis (TMA) to generate a firing solution for weapons systems (Jane’s Information Group, 2010).

The 89 system consists of 15 different variants. Variants differ based on the sensors chosen and the version of each sensor. In this report, only variants 2, 3, 4, 6, 7, and 9 were studied. These variants were chosen because they were on board ships prior to the introduction of CBT into the sonar training pipeline (2003) and remained on board after CBT was introduced. This allows for analysis of ship-maintenance trends both prior to and after the introduction of CBT. A list of ships per variant is given in Table 1.

Table 1. List of Ships and AN/SQQ-89(v) System Variants Used in This Study

(V)2	SHIP	HOMEPORT
CG 55	LEYTE GULF	Norfolk, VA
FFG 8	MCINERNEY	Mayport, FL
FFG 28	BOONE	Mayport, FL
FFG 29	STEPHEN W GROVES	Mayport, FL
FFG 32	JOHN HALL	Mayport, FL
FFG 33	JARRET	San Diego, CA
FFG 36	UNDERWOOD	Mayport, FL
FFG 38	CURTS	San Diego, CA
FFG 39	DOYLE	Mayport, FL
FFG 40	HALYBURTON	Mayport, FL
FFG 41	MCCLUSKY	San Diego, CA
FFG 42	KLAKRING	Mayport, FL
FFG 43	THACH	San Diego, CA
FFG 45	DE WERT	Mayport, FL
FFG 46	RENTZ	San Diego, CA
FFG 47	NICHOLAS	Norfolk, VA
FFG 48	VANDEGRIFT	San Diego, CA
FFG 49	ROBERT G BRADLEY	Mayport, FL
FFG 53	HAWES	Norfolk, VA
FFG 55	ELROD	Norfolk, VA
FFG 56	SIMPSON	Mayport, FL
FFG 57	REUBEN JAMES	Pearl Harbor, HI
FFG 58	SAMUEL B ROBERTS	Mayport, FL
FFG 59	KAUFFMAN	Norfolk, VA
FFG 60	RODNEY M. DAVIS	Everett, WA
FFG 61	INGRAHAM	Everett, WA

(V)3	SHIP	HOMEPORT
CG 56	SAN JACINTO	Norfolk, VA
CG 57	LAKE CHAMPLAIN	San Diego, CA
CG 58	PHILIPPINE SEA	Mayport, FL

(V)4	SHIP	HOMEPORT
DDG 51	ARLEIGH BURKE	Norfolk, VA

(V)7	SHIP	HOMEPORT
CG 66	HUE CITY	Mayport, FL
CG 67	SHILOH	Yokosuka, Japan

(V)9	SHIP	HOMEPORT
FFG 37	CROMMELIN	Pearl Harbor, HI
FFG 50	TAYLOR	Mayport, FL
FFG 51	GARY	San Diego, CA
FFG 52	CARR	Norfolk, VA
FFG 54	FORD	Everett, WA

(V)6	SHIP	HOMEPORT
CG 68	ANZIO	Norfolk, VA
CG 69	VICKSBURG	Mayport, FL
CG 70	LAKE ERIE	Pearl Harbor, HI
CG 71	CAPE ST GEORGE	San Diego, CA
CG 72	VELLA GULF	Norfolk, VA
DDG 52	BARRY	Norfolk, VA
DDG 53	JOHN PAUL JONES	San Diego, CA
DDG 54	CURTIS WILBUR	Yokosuka, Japan
DDG 55	STOUT	Norfolk, VA
DDG 56	JOHN S. MCCAIN	Yokosuka, Japan
DDG 57	MITSCHER	Norfolk, VA
DDG 58	LABOON	Norfolk, VA
DDG 59	RUSSELL	Pearl Harbor, HI
DDG 60	PAUL HAMILTON	Pearl Harbor, HI
DDG 61	RAMAGE	Norfolk, VA
DDG 63	STETHEM	Yokosuka, Japan
DDG 64	CARNEY	Mayport, FL
DDG 65	BENFOLD	San Diego, CA
DDG 66	GONZALEZ	Norfolk, VA
DDG 67	COLE	Norfolk, VA
DDG 68	THE SULLIVANS	San Diego, CA
DDG 69	MILIUS	San Diego, CA
DDG 70	HOPPER	Pearl Harbor, HI
DDG 71	ROSS	Norfolk, VA
DDG 72	MAHAN	Norfolk, VA
DDG 73	DECATUR	San Diego, CA
DDG 74	MCFAUL	Norfolk, VA
DDG 75	DONALD COOK	Norfolk, VA
DDG 76	HIGGINS	San Diego, CA
DDG 77	O'KANE	Pearl Harbor, HI
DDG 78	PORTER	Norfolk, VA

All sonar technicians–surface (STGs) attend STG A school. At A school, students learn the basic principles of the STG rating including oceanography and principles of sound. Following A school, STGs are sent to different courses depending on whether they are operators or operator/maintainers. STGs who are strictly operators are sent to a sonar operator course, where they learn how to operate the specific 89 variant of the ship to which they will be sent. Maintainers are sent to C school, where they learn the technical skills required to maintain the equipment they will work on upon reporting to their ship (Navy Personnel Command, 2012).

CBT was introduced full-time into the training pipeline in FY2003, after the recommendations of the ERNT report (Naval Inspector General, 2009). Data were not available to show how STG course lengths were affected by the conversion to CBT. The 2009 Navy IG report examined the course lengths of 22 A and C schools for ILT and CBT and found that on average, CBT course lengths were 26% shorter than ILT course lengths (Naval Inspector General, 2009). This study focuses on FY1999 through FY2010 to capture data prior to and after the introduction of CBT. Initially, FY1995 through FY1998 were also considered, but there were not enough data available during this time frame for most data categories. The raw data provided were analyzed to reveal relationships between selected data sets.

Program Executive Office Integrated Warfare System 5 (PEO IWS5) provided a list of ships equipped with the AN/SQQ-89(v) sonar system. The list included ship class, ship name, hull number, homeport, and 89 variant number. Only ships with AN/SQQ-89(v) variants on board both before and after implementation of CBT were considered. The initial list provided by PEO IWS5 included all ships of the CG-47, DD-963, DDG-51, and FFG-7

classes. To narrow the ship list to match the scope of our study, ships were removed from the data set if

- the ship was decommissioned during the FY1995-FY2006 time frame,
- the ship received a variant upgrade,
- the ship was commissioned FY2000 or later, or
- the ship was outfitted with a variant introduced after FY2003.

Using these criteria, the ship list was reduced to 68 ships. VAMOSC provided O&S cost data, underway steaming days, and selected non-cost data for ships equipped with the AN/SQQ-89 sonar system covering FY1995 through FY2010. Cost figures were given in then-year and constant FY2011 dollars.

In addition to the overall 89 system data, detailed ship data were available for the selected ships. Non-cost data included number of personnel trained, maintenance manhours, and number of maintenance actions. The data were used to calculate average time (in manhours) spent per maintenance action. These numbers were calculated to determine training and maintenance trends pre- and post-CBT (see Figure 1). For instance, if the average time spent per maintenance action increased, it could suggest a backlog of maintenance or a lack of technical competence in performing a maintenance action. Prior to CBT, manhours spent per maintenance action were trending upward; after the introduction of CBT, manhours per maintenance action remained relatively flat. This suggests that manhours per maintenance action may have reacted positively to the conversion to CBT; however, this assumes that the types of maintenance actions performed remained relatively constant.

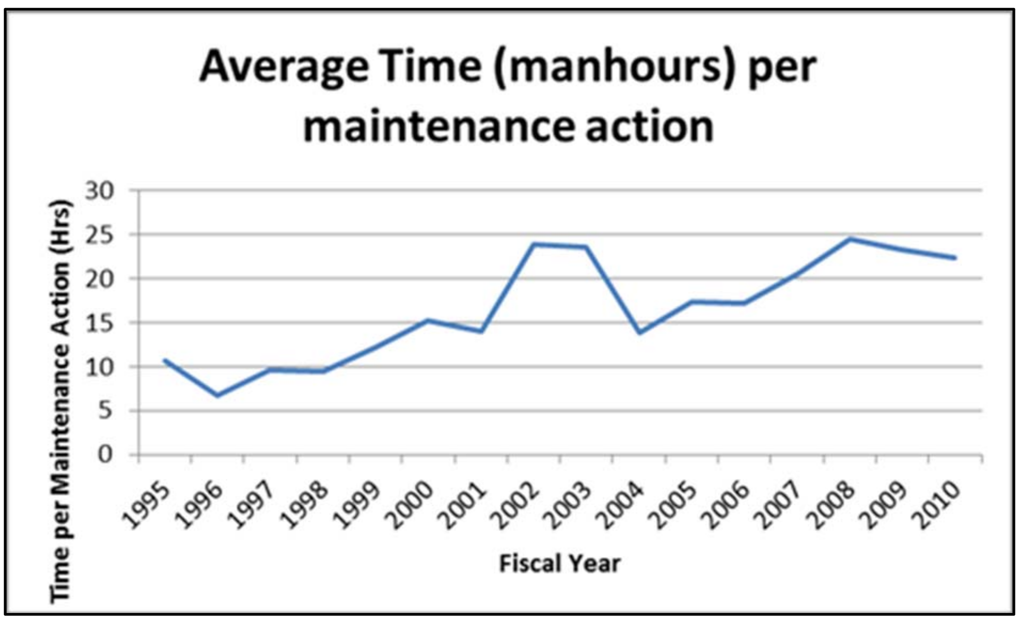

Figure 1. Manhours Spent per Maintenance Action

Single-factor regression analysis was performed to explore the relationship between total training cost and the O&S variables provided by Navy VAMOSC. Unit Level Consumption, IM, Equipment Rework, and Depot Maintenance were selected as variables to determine whether changes in training costs resulted in increased maintenance costs. The selected variables represent organizational-level, intermediate, and depot-level

maintenance. Unit Level Consumption is a summation of Organizational Repair Parts, Replenishment Spares, and Logistics Center (LOGCEN) exchanges. Equipment Rework is a summation of contractor and government Program Office rework costs. IM is a summation of afloat and ashore IM labor costs and ashore IM materials costs. Depot Maintenance is a summation of private and public shipyard depot costs. Training (Total) is a summation of Program Office and NETPDTC training costs. The results are shown in Table 2.

Table 2. Regression Analysis—O&S Components

	R^2
Unit Level Consumption	0.033
Equipment Rework	0.002
Intermediate Maintenance	0.348
Depot-Level Maintenance	0.208

In this case, regression analysis shows that none of the factors selected have a strong relationship to total training cost, suggesting that if maintenance costs are related to training costs in the STG rating, there are other factors not identified in this study that are having an effect. It is interesting to look at the relationship of IM costs and training dollars in a scatter diagram (Figure 2).

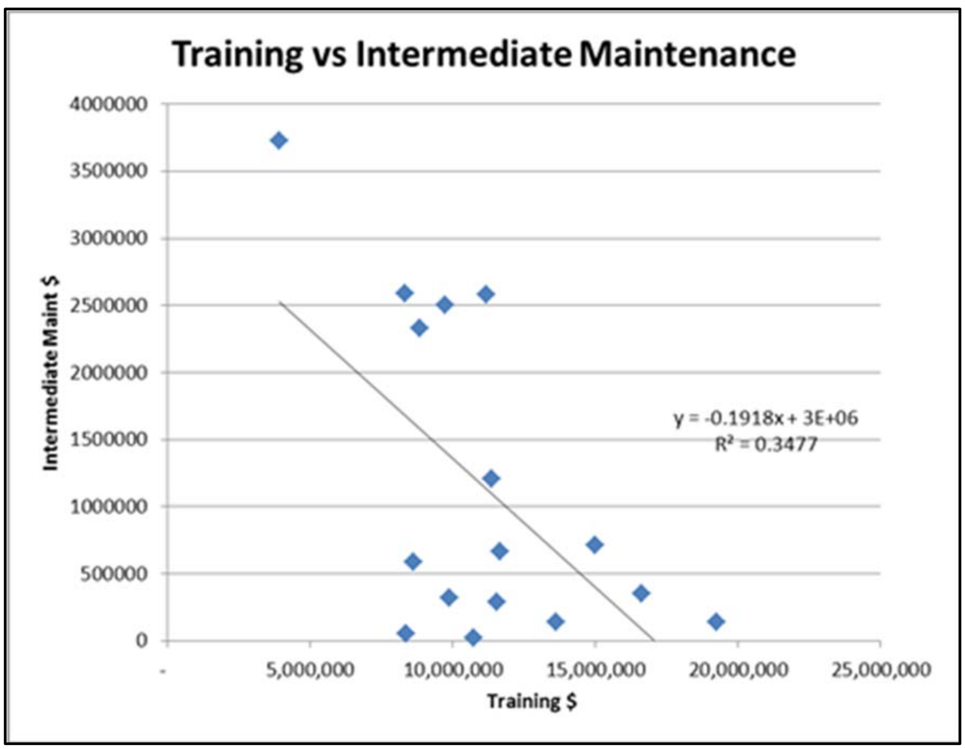

Figure 2. Training vs. Intermediate Maintenance Scatter Plot

Figure 2 suggests that there may be a weak relationship between training dollars and intermediate maintenance costs and that this warrants further investigation. Specifically, the

plot suggests that as training costs increase, intermediate maintenance costs decrease. This would support the hypothesis that when less money is spent on training (as a result of switching to CBT), the maintenance costs will increase.

Graphical analysis of several data categories indicated noticeable changes after the introduction of CBT. For example, Labor Ashore—Intermediate Maintenance Manhours showed significant change (see Figure 3).

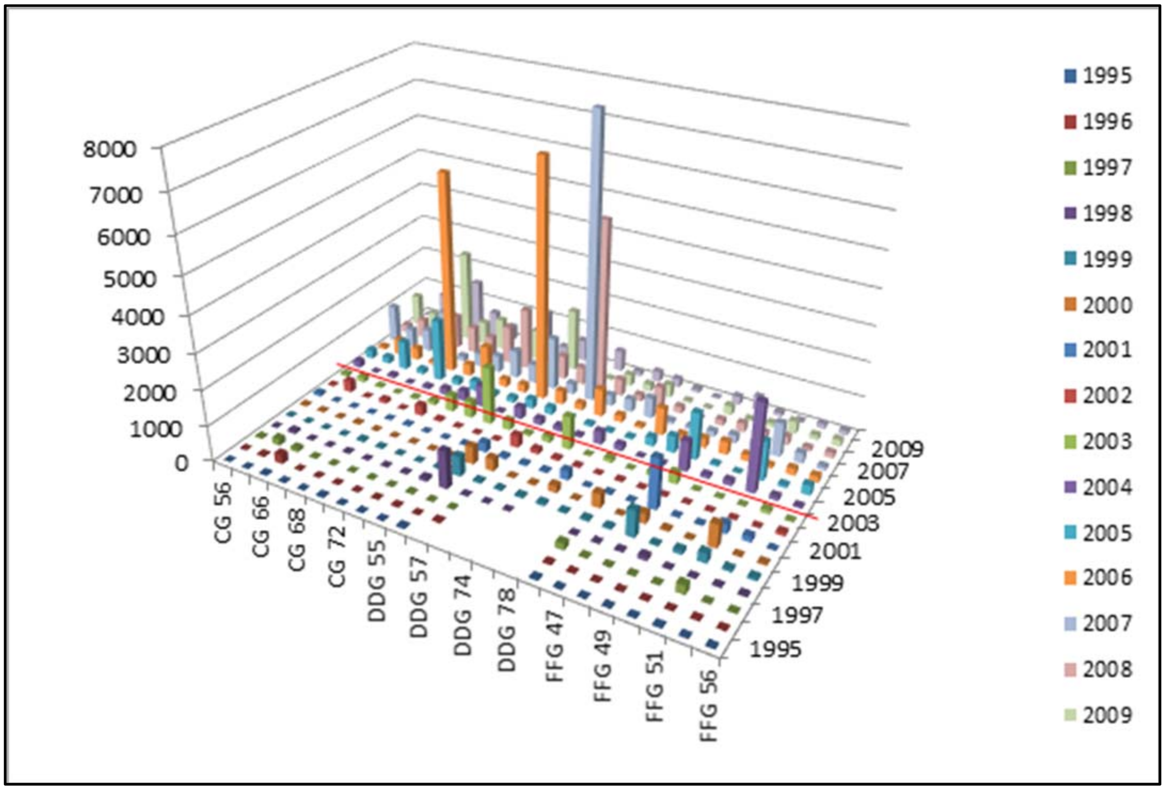

Figure 3. Labor Ashore—Intermediate Maintenance Manhours

The figure shows the number of manhours spent on IM for selected ships from FY1995 through FY2010. Beginning in FY2004, the IM manhours increased significantly for the selected DDG-51 and CG-47 class ships. While this may be partially explained by changes to Navy maintenance policy described earlier, it corroborates the evidence suggested in Figure 2, namely that as CBT is introduced and training costs decrease, intermediate maintenance hours and cost increase. This trend was not as evident, however, for the FFG-7 class. This may be explained by funding of the ship class, since many of these ships belong to the Naval Reserve Force and it is likely that their funding levels did not change throughout the period studied.

Paired t-tests were conducted to determine whether the means of paired observations (selected ships pre- and post-CBT) were different. The null hypothesis is that there is no significant difference in the means before and after the introduction of CBT. The alternate hypothesis is that there is a significant difference between the means due to CBT. A negative t-statistic indicates that the pre-CBT mean was smaller, while a positive t-statistic indicates that the post-CBT mean was smaller. Response variables used in this study were corrective organizational and IM actions, organizational parts cost, exchanges LOGCEN cost, manhours organizational labor, and labor ashore IM manhours (see Table 3).

Table 3. Paired t-Test Results

Variable	degrees freedom		Number of obs.	Mean	t statistic	p-value
Corrective org. & IM actions	786	before CBT	335	61.43	-6.61	0.0000
		after CBT	458	85.10		
Organizational parts cost	790	before CBT	336	6914.4	-4.07	0.0000
		after CBT	466	9539.6		
Exchanges LOGCEN cost	563	before CBT	238	43752	-6.30	0.0000
		after CBT	328	72178		
Manhours org. labor	779	before CBT	335	739.9	-7.03	0.0000
		after CBT	466	1208.7		
Labor ashore IM manhours	206	before CBT	109	107.51	-5.17	0.000
		after CBT	149	357.17		

In all cases, the p-values were less than 0.01, indicating a significant difference between the means pre- and post-CBT. This suggests that the introduction of CBT had a statistically significant impact on several measures of maintenance activity and cost.

Interestingly, the number of maintenance actions (organizational and IM) increased, even though changes in Navy maintenance policies would have initially led to fewer maintenance actions. Since we report the average over several years, it is possible that the expected increase in future maintenance actions was part of the observed mean after CBT. It is also likely that changes in operating tempo (due to the GWOT) had a significant impact on this variable as well, so it is not possible to isolate the effect of CBT on corrective maintenance actions.

Most interesting are the three categories related to maintenance actions performed by sailors at the ship level: organizational parts cost, exchanges LOGCEN cost, and manhours organizational labor. If the conversion to CBT were to have an effect anywhere in the Navy maintenance system, it would be at maintenance activities where sailors were performing maintenance on ships. This data would support the anecdotal evidence provided by ship operators that CBT training would also impact labor ashore IM manhours (in IM facilities); however, a confounding variable for IM is that several shore-based IM facilities were closed and shore-based IM billets for sailors were eliminated.

Conclusion and Areas for Further Research

In 2001, ERNT released its report, Rev*olution in Training: Executive Review of Navy Training Final Report*, which led to a major overhaul in the U.S. Navy's training practices, including the use of CBT in A and C schools. While government studies of the Navy's CBT training confirmed that the transition to CBT resulted in shorter training times and cost savings, sailors reporting to the fleet were not as well prepared as classroom-trained sailors of the past, and extensive OJT, supervision, and assistance in performing basic maintenance tasks were required to bring CBT-trained sailors up to speed.

During the same period of time that CBT was being implemented, the U.S. Navy reorganized its maintenance program and reduced total manning levels on ships, even though ship requirements did not change, meaning that ships had to do more work with fewer personnel. Many maintenance requirements were deferred or eliminated on ships with

the expectation that shore facilities would pick up the slack, but shore facilities also experienced manning reductions. As a result, less planned maintenance was being performed on equipment, which increased opportunities for equipment failure and decreased fleet material readiness.

This study looked at costs from a systems perspective, considering not only the cost of training but also the cost of maintenance. We asked the following question: If sailors trained with CBT had lower knowledge and skill levels, did this contribute to increased operations and maintenance costs?

Unfortunately, there were too many confounding variables that could have affected operation and maintenance costs during this period of time to draw any conclusions about the effect of CBT on maintenance costs from the Navy level. Instead, we focused on a single Navy system, the AN/SQQ-89(v) sonar system, to examine the effects of the conversion to CBT on maintenance.

The results of the study revealed several pieces of useful information. Regression analysis indicates a weak relationship between decreasing in training costs and an increasing in IM costs. In addition, paired t-tests showed that the conversion to CBT may have led to increases in corrective organizational and IM actions, organizational parts cost, exchanges LOGCEN cost, manhours organizational labor, and labor ashore IM manhours. Of particular interest were results for manhours organizational labor, organizational parts cost, and exchanges LOGCEN cost, all associated with maintenance performed by sailors at the unit (ship) level, because conversion to CBT training would be most noticeable at maintenance activities where sailors are performing the maintenance.

As the Navy IG, GAO, and Balisle reports suggest, there are several factors that have contributed to declines in fleet readiness. Most notably, the simultaneous combination of changes in training, maintenance, and manning policies appear to have had lasting negative impacts, including rising fleet maintenance costs. The data analysis performed in this study shows that the change to CBT was statistically significant when compared to several maintenance variables, but it is also likely that changes to all three areas (training, maintenance, and manning) had collective negative effects which go much further than rising maintenance costs and actions. It is clear that policy changes in the 2000s impacted fleet readiness in a negative manner, but no clear conclusions can be drawn about the specific impact of CBT on total system cost from the data examined in this study.

Because the data collected can be characterized as panel data, statistical analysis that recognizes the panel nature of the data will be performed and reported in another paper. It may be useful to study the impacts of the conversion to CBT on other Navy systems. From a training perspective, the lack of measures of effectiveness for training may prove frustrating in drawing any conclusions, but from a cost perspective, it may be possible to gain further insight into the types of cost most affected by CBT.

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The GAO's 11th Annual Assessment of Selected Weapon Programs

Michael J. Sullivan—Sullivan is the director, Acquisition and Sourcing Management, U.S. Government Accountability Office. This group has responsibility for examining the effectiveness of the DoD's acquisition and procurement practices in meeting its mission performance objectives and requirements. In addition to directing reviews of major weapon system acquisitions such as the Joint Strike Fighter, F-22, Global Hawk, and various other major weapon acquisition programs, Sullivan has developed and directs a body of work examining how the DoD can apply best practices to the nation's largest and most technically advanced weapon systems acquisition system. This work has spanned a broad range of issues critical to the successful delivery of systems, including technology development, product development, transition to production, software development, program management, requirement-setting, cost estimating, and strategic portfolio management. The findings and recommendations from this work have played a major role in the department's recent acquisition policy revisions. Most recently, he has directed the GAO's annual assessment of major weapon systems programs for the Congress and GAO's work with Congress in establishing acquisition policy reforms. His team also provides the Congress with early warning on technical and management challenges facing these investments. Sullivan has been with the GAO for 24 years. He received a bachelor's degree in political science from Indiana University and a master's degree in public administration from the School of Public and Environmental Affairs, Indiana University. [sullivanm@gao.gov]

Abstract

This paper reflects the GAO's observations on how well the DoD is planning and executing its $1.602 trillion portfolio of major weapon programs. Although the total projected cost of the portfolio remains significant, that cost has declined since peaking at $1.75 trillion in 2010 and is currently at its lowest point in over five years. In addition, the number of programs in the portfolio has decreased from 98 programs in 2010 to 86 programs in 2012. DoD weapon system acquisition represents one of the largest areas of the government's discretionary spending. With the likelihood of decreased defense budgets looming in the near future, it is imperative that the DoD continue to find ways to reduce cost and improve efficiency.

Introduction

This paper reflects the GAO's observations on how well the DoD is planning and executing its $1.602 trillion portfolio of major weapon programs. Although the total projected cost of the portfolio remains significant, that cost has declined since peaking at $1.75 trillion in 2010 and is currently at its lowest point in over five years. In addition, the number of programs in the portfolio has decreased from 98 programs in 2010 to 86 programs in 2012. DoD weapon system acquisition—an area that has been on the GAO's high-risk list for more than 20 years—still represents one of the largest areas of the government's discretionary spending. Over the past decade, Congress and the DoD have made meaningful improvements in the statutory and policy frameworks that govern weapon system acquisitions by mandating and encouraging a more knowledge-based approach to the development and production of major systems. The GAO has noted in the past that practice has lagged behind policy in certain areas, and commensurate improvements in program outcomes have not been evident. However, the changes in the DoD's portfolio over the past few years indicate that some improvements are being realized. With the likelihood of decreased defense budgets looming in the near future, it is imperative that the DoD continue to find ways to reduce cost and improve efficiency.

The following are observations on (1) the cost and schedule performance of the DoD's 2012 portfolio of 86 major defense acquisition programs, including the Missile

Defense Agency's (MDA's) Ballistic Missile Defense System (BMDS); (2) the knowledge attained at key junctures in the acquisition process for 40 weapon programs in development or early production; and (3) key acquisition reform initiatives and program concurrency.[1] For a more detailed discussion of each of the observations, see GAO-13-294SP (GAO, 2013).

Data from three sets of programs provided the basis for the observations:

- We assessed all 86 major defense acquisition programs in the DoD's 2012 portfolio for our analysis of cost and schedule performance. To develop our observations, we obtained cost, schedule, and quantity data from the DoD's December 2011 Selected Acquisition Reports (SARs) and from the Defense Acquisition Management Information Retrieval Purview system. In order to fully reflect the total size and cost of the DoD's portfolio, we included the cost of BMDS—as of DoD's fiscal year 2013 budget submission—in this year's assessment of the changes in the overall cost and size of the portfolio over the past year. However, the program was excluded from the remainder of our analyses because no acquisition program baseline exists.
- We assessed 40 MDAPs that were mostly between the start of development and full-rate production for our analysis of knowledge attained at key junctures and the implementation of acquisition reforms. To develop our observations, we obtained information on the extent to which the programs follow knowledge-based practices for technology maturity, design stability, and production maturity using a data-collection instrument. We also submitted a survey to program offices to collect information on systems engineering reviews, design stability, manufacturing planning and execution, and the implementation of specific acquisition reforms. We received survey responses from all of the programs from August to November 2012.
- In addition, we assessed 17 future major defense acquisition programs in order to gain additional insights into the implementation of key acquisition reform initiatives. To develop our observations, we submitted a survey to program offices to collect information on program schedule events, costs, and numerous acquisition reforms, and received responses from all 17 future programs from August to October 2012.

Observations on the Performance of the DoD's 2012 Major Defense Acquisition Program Portfolio

The overall size and estimated cost of the DoD's portfolio of MDAPs decreased over the past year, while the average time to deliver initial capability to the warfighter increased by one month. Our analysis of the DoD's 2012 portfolio allows us to make the following nine observations.

1. The DoD's 2012 portfolio of major defense acquisition programs contains 86 programs with a combined total estimated cost of $1.602 trillion, which is a

[1] Major defense acquisition programs are those identified by the DoD that require eventual total research, development, test, and evaluation (RDT&E) expenditures, including all planned increments, of more than $365 million, or procurement expenditures, including all planned increments, of more than $2.19 billion, in fiscal year 2000 constant dollars. The DoD has a list of programs designated as pre–major defense acquisition programs (pre-MDAP). These programs have not formally been designated as MDAPs; however, the DoD plans for these programs to enter system development, or bypass development and begin production, at which point they will likely be designated as MDAPs. We refer to these programs as future major defense acquisition programs throughout this report.

reduction of 10 programs and more than $152 billion from 2011 levels. This represents the smallest portfolio in more than five years.[2]

2. The total estimated acquisition cost of the 86 programs in the 2012 portfolio decreased by $44 billion over the past year while the delivery of initial operating capability slipped by one month on average.[3] When assessed against first full estimates, the total cost of the portfolio has increased by over $400 billion, including more than $90 billion in development cost growth and nearly $290 billion in procurement cost growth, with an average delay of 27 months in the delivery of initial operating capability.[4]
3. Program cancelations and restructurings account for nearly all of the cost reduction over the past year.
4. Long-term progress of the Missile Defense Agency's $133 billion BMDS cannot be assessed because insight into future program costs is limited to the five years covered by the budget, and the program was not required to establish an acquisition program baseline when it began.
5. More than 60% of the programs in the 2012 portfolio increased buying power over the past year—as measured by a decrease in program acquisition unit cost—a notable improvement when compared to last year, when more than 60% of the programs in the portfolio lost buying power.
6. When measured against cost growth targets discussed by the DoD, the Office of Management and Budget (OMB), and the GAO, the portfolio's performance has improved. Only 15% of programs exceeded the one-year target—down from 40% last year—and smaller percentages of programs exceeded targets for growth both in the past five years and since first full estimates.
7. Eight of the 10 costliest programs in the DoD's portfolio, excluding BMDS, reported cost reductions over the past year totaling nearly $5 billion—about 10% of the portfolio's total cost reduction.
8. The DoD has invested more than $805 billion in its 2012 portfolio, leaving over $660 billion remaining to be funded, excluding BMDS. More than 90% of the remaining funding is for procurement, with more than 60% of that amount associated with the 10 costliest programs in the portfolio, most prominently the Joint Strike Fighter.
9. Around 40% of the funding needed to complete the programs in the portfolio represents cost growth since first full estimates.

Observations on Knowledge Attained by Programs at Key Acquisition Junctures

Our 2013 assessment continues to demonstrate both progress and a significant need for programs to better follow a knowledge-based approach, reducing gaps in technology, design, and production knowledge. Knowledge in these three areas builds over

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[2] All dollar figures are in fiscal year 2013 constant dollars, unless otherwise noted.
[3] In addition to research and development and procurement costs, total acquisition cost includes acquisition-related operation and maintenance and system-specific military construction costs.
[4] Our discussion of cost growth since first full estimates does not include the BMDS, as the program was not required to establish an acquisition program baseline when it began (see GAO, 2012a, for an assessment of the Missile Defense Agency's cost, testing, and performance progress in developing the system).

time—a knowledge deficit early in a program can cascade through design and production, leaving decision-makers with less knowledge to support decisions about when and how best to move into subsequent acquisition phases that commit more budgetary resources. A knowledge-based acquisition approach is a cumulative process in which certain knowledge is acquired by key decision points before proceeding. Demonstrating technology maturity is a prerequisite for moving forward into system development, during which the focus should be on design and integration. A stable and mature design is likewise a prerequisite for moving forward into production where the focus should be on efficient manufacturing. We assessed the knowledge attained at key junctures in the acquisition process for 40 individual weapon programs, which are mostly in development or early production.[5] Not all programs included in our assessment of knowledge-based practices provided information for every knowledge point or had reached all of the knowledge points—development start, design review, and production start—at the time of our review. Our analysis allows us to make the following three observations:

1. Many of the programs that began in the last five years had mature technologies and held a preliminary design review prior to the start of development (knowledge point 1), providing a better foundation to avoid future cost and schedule problems.
2. Less than one third of the programs that provided data on design drawings released actually reported having a stable design at their critical design review (knowledge point 2), and the use of other knowledge-based practices to ensure design stability at this critical juncture varied.
3. Many of the programs we assessed have taken or plan to take steps to capture critical manufacturing knowledge prior to the start of production (knowledge point 3), although the methods used varied.

Observations on Implementation of Acquisition Reform Initiatives and Program Concurrency

Over the past several years, Congress and the DoD have instituted multiple initiatives aimed at improving the way the department does business by driving down acquisition costs and ensuring that programs are more affordable: specifically the Weapon Systems Acquisition Reform Act of 2009, the reissuance of DoD Instruction 5000.02 (OUSD[AT&L], 2008), and multiple “Better Buying Power” memorandums issued by the Under Secretary of Defense for Acquisition, Technology, and Logistics (OUSD[AT&L], 2010a, 2010b, 2010c, 2012). We analyzed survey data collected from 40 current major defense acquisition programs—the same programs reflected in our knowledge point analysis—and 17 programs identified by the DoD as future major defense acquisition programs, regarding the implementation of key aspects of these reform initiatives. We focused our analysis on the aspects of the DoD’s “Better Buying Power” initiatives and the Weapon Systems Acquisition Reform Act of 2009 aimed at ensuring program and portfolio affordability, controlling cost growth, and promoting competition throughout the acquisition life-cycle.[6] In addition, we assessed the amount of concurrency between developmental

[5] Because knowledge points and best practices differ for shipbuilding programs, we exclude the six shipbuilding programs from some of our analysis related to knowledge point 2 and knowledge point 3.
[6] In December 2012, we reported on the DoD’s implementation of the Weapon System Acquisition Reform Act of 2009 and noted that the DoD had taken steps to implement fundamental provisions of the Act, and that the DoD was taking additional steps to further strengthen its policies and acquisition capabilities. We also reported, however, that the DoD still faced organizational, policy, and cultural challenges to implementing acquisition reform (GAO, 2012b).

testing and production for those current programs beyond knowledge point 3.[7] We have consistently emphasized the importance of completing developmental testing before entering production and have pointed out the increased risks associated with concurrent testing and production. Our analysis allows us to make the following five observations:

1. The implementation of several key initiatives in the Weapon System Acquisition Reform Act of 2009 aimed at increasing program knowledge at development start varied among the future major defense acquisition programs we surveyed.
2. Around half of the current and future programs we assessed have established affordability requirements, and many are meeting those requirements.
3. Almost 90% of the current MDAPs we assessed have conducted “should cost” analysis, and most of those programs noted that they had realized or expected to realize cost savings as a result.
4. Although the DoD recognizes the need for and benefits of competition in weapon system acquisitions, and the Weapon Systems Acquisition Reform Act of 2009 requires programs to have competitive acquisition strategies, many of the programs we assessed did not have such strategies in place.
5. Nearly 80% of the programs we surveyed that were in production reported that 30% or more of their developmental testing had been or was going to be done during production, despite the increased risk that design changes and costly retrofits will need to be made.

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Weapon Systems Acquisition Reform Act of 2009, Pub. L. No. 111-23 (2009).

[7] This analysis reflects 18 non-ship programs, of the 40 total, for which we have a knowledge point 3 date identified. Ships are excluded from this analysis because we do not assess knowledge point 3 for ships.

Contract Management

Services Supply Chain in the Department of Defense: Defining and Measuring Success of Services Contracts in the U.S. Navy

Uday Apte and Rene Rendon
Naval Postgraduate School

Make or Buy: A Systematic Approach to Department of Defense Sourcing Decisions for Services (An Interim Report)

Jesse Ellman, Joachim Hofbauer, David J. Berteau, and Guy Ben-Ari
Defense-Industrial Initiatives Group, Center for Strategic and International Studies

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Services Supply Chain in the Department of Defense: Defining and Measuring Success of Services Contracts in the U.S. Navy

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Abstract

DoD spending on services has been trending upwards for over a decade and, as of 2011, it accounted for 56% of total contract spending. The increased reliance on services contractors has prompted the GAO to look more closely at the acquisition and contract management process. In this research, we address the following questions: (1) How do different stakeholders define successful services contracts within the Navy? (2) How do different stakeholders measure services contracts within the Navy? and (3) How should Navy services contracts be defined and measured? We conducted a survey of 168 key stakeholders. We discovered that when defining and measuring the success of a service contract, all stakeholders tend to utilize outcome-related factors over process-oriented factors. We believe this is because outcomes tend to drive perceptions of success more than processes and are more easily quantifiable. Metrics used to measure success are typically related to cost, schedule, and performance. Based on these findings, we provide recommendations on establishing better internal control measures, putting in place an operational audit process, and creating a standardized reporting process.

Introduction

The service sector represents the largest and the fastest growing segment of the economies of the U.S. and other developed countries. This growth of services in the overall economy is also mirrored by the growth of services acquisition in the DoD. For example, the DoD obligations on contracts have more than doubled between fiscal years 2001 and 2008 to over $387 billion, with over $200 billion spent just for services in 2008 (GAO, 2009). In conjunction with this increase in defense procurement is the reduction of the defense acquisition workforce. The size of the federal workforce decreased from 2.25 million in 1990 to 1.78 million in 2000 (GAO, 2002). The combination of the increasing defense procurement workload and the decreasing size of the government workforce, along with the complexities of an arcane and convoluted government contracting process, have created the perfect storm—an environment in which complying with government contracting policies and adopting contract management best practices has not always been feasible (Rendon, 2010). Between 2001 and 2009, the GAO issued 16 reports related to trends, challenges, and deficiencies in defense contracting. During this same time frame, the DoD Inspector

General (DoDIG) issued 142 reports on deficiencies in the DoD acquisition and contract administration processes. These reports have identified poor contract planning, contract administration, and contractor oversight as just some of the critically deficient areas in DoD contract management. Because of these deficiencies, the GAO has identified contract management as a “high risk” area for the federal government since 1990 and continues to identify it as high risk (GAO, 2013).

As the DoD’s services acquisition continues to increase in scope and dollars, the agency must give greater attention to proper acquisition planning, adequate requirements definition, sufficient price evaluation, and proper contractor oversight (GAO, 2002). In fact, as stressed in a recent memorandum for acquisition professionals by the Under Secretary of Defense for Acquisition, Technology, and Logistics (USD[AT&L], 2010), improving the efficiency of the acquisition of products and services is of utmost importance to the DoD. In some ways, the issues affecting services acquisition are similar to those affecting the acquisition of physical supplies and weapon systems. However, the unique characteristics of services and the increasing importance of services acquisition offer a significant opportunity for conducting research in the management of services acquisition in the DoD.

Research Questions

This research project undertakes a focused, in-depth study of the services acquisition so as to understand how success of service acquisition contracts is being defined and measured in the Navy. The contract management process is performed with inputs from the different functional areas, such as program management, contracting, financial, logistics, and quality assurance. Each of these project team members represents different stakeholders and are therefore likely to have different goals and objectives. Hence, the first research question we investigated was as follows: How do different stakeholders define successful services contracts within the Navy? To develop a clear understanding of current services acquisition practices, we also investigated the second research question: How do different stakeholders measure services contracts within the Navy? Investigating the previous two questions helped us develop recommendations regarding the third and final research question: How should the service contract’s success be measured? The next section provides a literature review of some of the management theories informing service supply chain management, as well as some of our previous research on DoD services acquisition.

Literature Foundation

The academic research in the management of services acquisition is founded on several economic and management theories, including agency theory (Eisenhardt, 1989), transaction cost economics (Williamson, 1979), contractual theory (Luo, 2002), service operations and supply management (Fitzsimmons & Fitzsimmons, 2006), and stakeholder theory (Freeman, 1984; Cleland,1986; El-Gohary, Osman, & El-Diraby, 2006). We refer the reader to our earlier technical report (Apte & Rendon, 2013) for a survey of prior academic research, and we also provide a summary of research projects carried out by the authors in the area of services supply chain.

We have addressed the need for research in this increasingly important area of services acquisition by undertaking six sponsored research projects over the past six years. The first two research projects (Apte, Ferrer, Lewis, & Rendon, 2006; Apte & Rendon, 2007) were exploratory in nature, aimed at understanding the types of services being acquired, the associated rates of growth in services acquisition, and the major challenges and opportunities present in the service supply chain.

The next two research projects were survey-based empirical studies aimed at developing a high-level understanding of how services acquisition is currently being managed at a wide range of Army, Navy, and Air Force installations (Apte, Apte, & Rendon, 2008; Apte, Apte, & Rendon, 2009). The analysis of survey data indicated that the current state of services acquisition management suffers from several deficiencies, including deficit billet and manning levels (which are further aggravated by insufficient training and the inexperience of acquisition personnel) and the lack of strong project-team and life-cycle approaches. Our research (Apte, Apte, & Rendon, 2010) also analyzed and compared the results of the primary data collected in two previous empirical studies involving Army, Navy, and Air Force contracting organizations so as to develop a more thorough and comprehensive understanding of how services acquisition is being managed within individual military Services.

As a result of these research projects dealing with the service supply chain in the DoD, we have developed a comprehensive, high-level understanding of services acquisition in the DoD, have identified several specific deficiencies, and have proposed a number of concrete recommendations for performance improvement.

Based on the foundation of the previously mentioned management theories, conclusions of the GAO and DoDIG reports (Seifert & Ermoshkin, 2010), and findings of our own sponsored research projects on the topic, we believe that the success of service acquisition contracts is significantly influenced by four broadly defined factors: (1) the type and quantity of services being outsourced and the associated amount of acquisition-related workload; (2) the characteristics of contracts being awarded; (3) the capacity available to carry out the contracting, project management, and surveillance work; and (4) various management practices, such as use of project team or life-cycle approaches and so forth. A conceptual model indicating the interrelationship among these factors is shown in Figure 1.

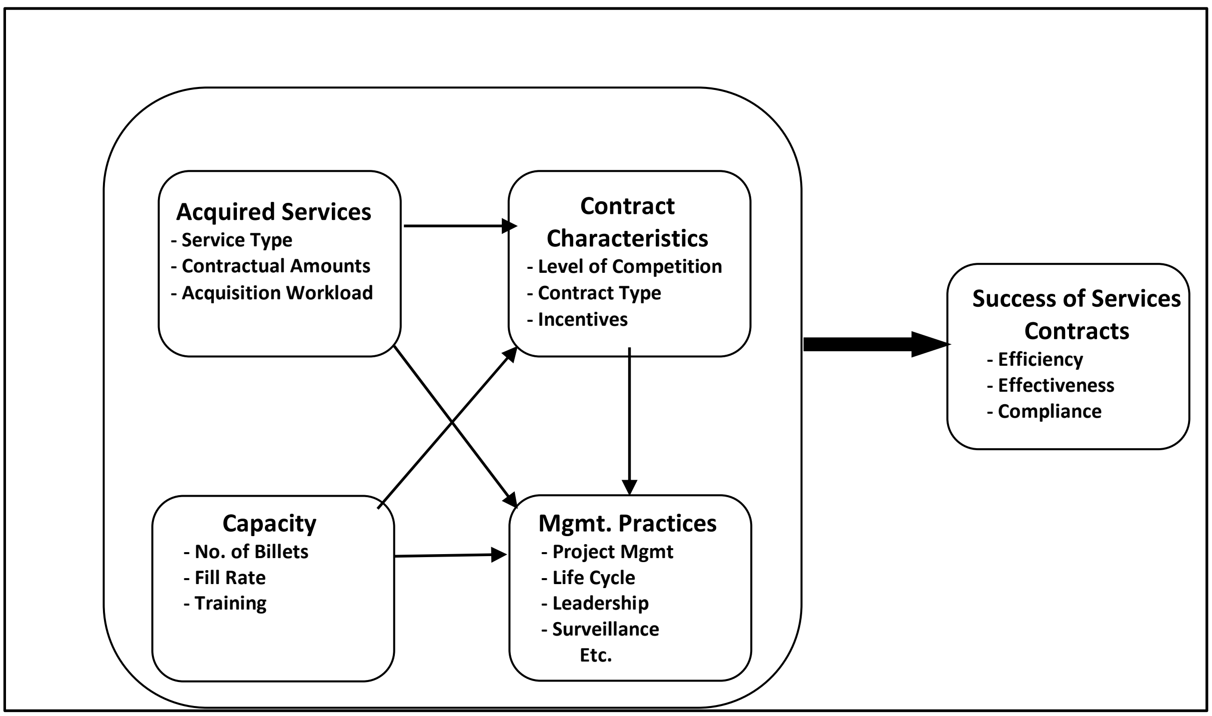

Figure 1. Drivers of Acquisition Practices and Success of Service Contracts

As shown in the conceptual diagram of Figure 1, the contract characteristics are affected by the type of service being acquired, while the management practices being used are influenced by the services being acquired, the contract characteristics, and, more importantly, the capacity available to perform the acquisition work. The success of services contracts, in turn, is affected by the previously mentioned four drivers. Underlying Figure 1 is the fundamental question motivating our in-depth research: What drives the success of services contracts? This fundamental question is, of course, critically important, and yet it is also not one that can be answered easily or quickly. We believe that, generally, in the case of questions related to complex systems, it is preferable to break down the overall system in smaller parts, gain an understanding of the functioning of each part, and then put all the pieces together to better understand the overall system and answer the fundamental question. That is what we plan to do in this research by addressing three research questions: (1) understand how the success of services contracts is being defined by different stakeholders, (2) identify how the success of services contracts is currently being measured, and (3) develop specific recommendations on how the success of services contracts should be measured. We address our research methodology in the next section.

Research Methodology

With the assistance of our MBA thesis students (Hagan, Spede, & Sutton, 2012), we developed and deployed a data collection survey instrument to collect empirical data for answering our research questions. The survey was deployed to the various stakeholders at the participating commands. We then analyzed the data using descriptive statistics to provide recommendations and conclusions.

We developed and deployed a web-based survey using the SurveyMonkey website. The survey instrument included both demographic questions and core questions related to defining and measuring successful services contracts. The core questions were designed to establish the importance of different factors when defining and measuring the success of services contracts. These core questions were related to the contracting process, as well as to different outcomes such as cost, schedule, and performance (Hagan et al., 2012).

In terms of defining successful contracts, the core questions asked participants to rank various definitions relating to the four metrics (process, cost, schedule, and performance) in order of most important (1) to least important (5). We also asked participants to rate definition statements relating to process, cost, schedule, and performance. These questions use a Likert scale asking level of agreement, importance, and amount of time devoted by the participants. The Likert scale had a range of 1 to 5, with 1 representing a negative response and 5 representing a positive response (Hagan et al., 2012).

In terms of measuring successful contracts, the core questions asked participants to rank various measurements relating to the four metrics in order of most important (1) to least important (5). The last question in the section asks participants to rate on a Likert scale how often the organization conducts certain actions that pertain to the measurement of success concerning process, schedule, cost, and performance. Figure 2 reflects our survey question approach (Hagan et al., 2012).

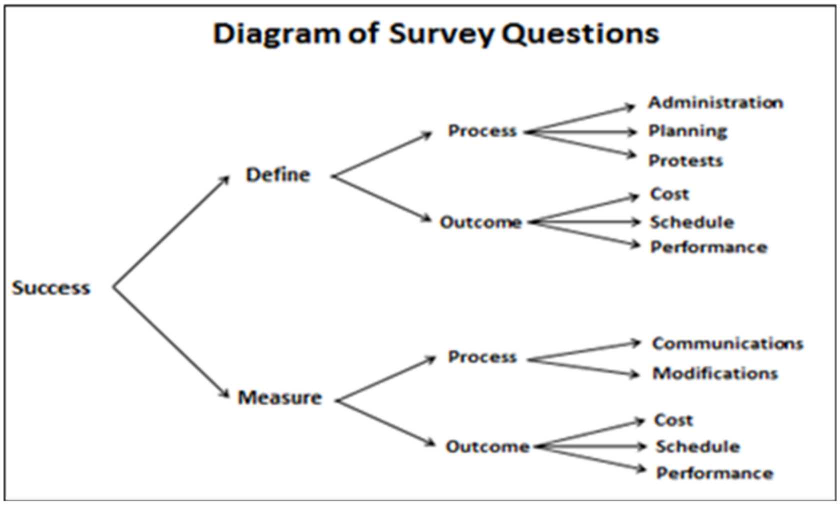

Figure 2. Diagram of Survey Questions

The survey was deployed to the major stakeholders (PMs, COs, and CORs) at the following major contracting commands: Fleet Logistics Center (FLC) Philadelphia, FLC Jacksonville, FLC Norfolk, FLC Puget Sound, FLC San Diego, Naval Sea Systems Command (NAVSEA), Military Sealift Command (MSC), and Space and Naval Warfare Systems Command (SPAWAR; Hagan et al., 2012).

Survey Results and Analysis

In this section, we present the results of the survey and discuss its major findings. As mentioned previously, the primary objective of this research is to empirically examine how the success of a service contract is being defined and measured by different stakeholders. We designed a survey containing 19 questions and distributed them to the major stakeholders in the services acquisition process to receive their responses. The survey was deployed at the eight Navy installations identified previously. We distributed the survey to a total of 843 respondents responsible for various acquisition-related functions. Specifically, we surveyed the following stakeholders: program manager/project officer, contract officer/contract specialist, contracting officer representative, requirements manager, financial manager, contractor, and customer. The survey questions included both Likert-type as well as ranking-type questions. The Likert-type questions were used to assess favorable or unfavorable responses, while the ranking-type questions were used to assess the most important responses. When we examine the ranking questions in this section, the term “most important” refers to the number of factors that received the highest rankings of 1 or 2. We believe that this is the best way to capture and succinctly represent the participants’ responses. For example, a COR may feel that the outcome-related factors are extremely important and, therefore, should be given the highest ranking of 1 every time. However, the COR may also believe that the process-related factors are very important, too, and hence may assign the next highest rank of 2 to those factors. Hence, we believe that the percent of respondents giving a rank of 1 or 2 to a factor is the most effective way to capture and represent the importance of that factor while analyzing the data on ranking of factors.

The survey response rates we experienced for different categories of stakeholders are shown in Table 1. Unfortunately, we received only a small number of responses from requirements managers, financial managers, contractors, and customers. Hence, their responses are not incorporated in this report for analysis purposes. These respondents are combined under the “other” category in Table 1.

Table 1. Survey Response Rate

STAKEHOLDER	# SURVEYS DEPLOYED	# SURVEYS ANSWERED	RESPONSE RATE
PROGRAM MANAGER/PROJECT OFFICER	94	15	16%
CONTRACTING OFFICER REPRESENTATIVE	104	27	26%
CONTRACTING OFFICER/ CONTRACT SPECIALIST	280	126	45%
AGGREGATE DATA (PM, COR, PCO)	478	168	35%
OTHER	365	10	2.7%
TOTAL	843	178	21%

We present the survey results and analysis in three sub-sections: the first sub-section presents the aggregate data, the second sub-section presents the stakeholder-level data, and the third sub-section presents the service-type data.

Survey Results: Aggregate Survey Data

Defining the Success of a Service Contract

In taking a high-level view of our survey findings, we did not differentiate between functional roles, DAWIA levels of certification, type of service being acquired, contract type, or the organization. However, we did separate our findings under the broad categories of process and outcome. Outcome results included the questions associated with cost, schedule, and performance. As shown in Table 1, collectively, there were 168 responses from PMs, CORs, or PCOs. The Likert scale responses were assigned a value of 1 through 5, with the higher value representing a more favorable response to a statement. A summary of aggregate data about defining and measuring the success of a service contract is presented in Tables 2 and 3 of Appendix A. We examined the mean of responses to each set of Likert scale-type questions. We found that when defining the success of a services contract, outcomes are considered slightly more important than processes. The overall mean of responses related to outcomes was 4.08, while process responses resulted in a mean of 3.97. Our findings are displayed graphically in Figure 3.

We then separated our findings further within the broad category of outcomes into the narrower categories of cost, schedule, and performance. Performance-related questions resulted in the highest mean of 4.29, while cost-related questions produced a mean of 4.03, and schedule-related questions produced a mean of 3.93.

One hundred and sixty-eight respondents were asked to rank different factors related to defining the success of a service contract. These questions also dealt with different aspects of processes and outcomes. Of the 168 respondents, 40% felt that process-related factors were the most important. Sixty percent felt that outcome-related factors were the most important. The distribution of highest ranked responses is displayed in Figure 4.

Breaking down the outcome-related factors further, 15% of respondents felt that cost-related factors were the most important, 19% felt that schedule-related factors were most important, and 26% felt that performance-related factors were most important.

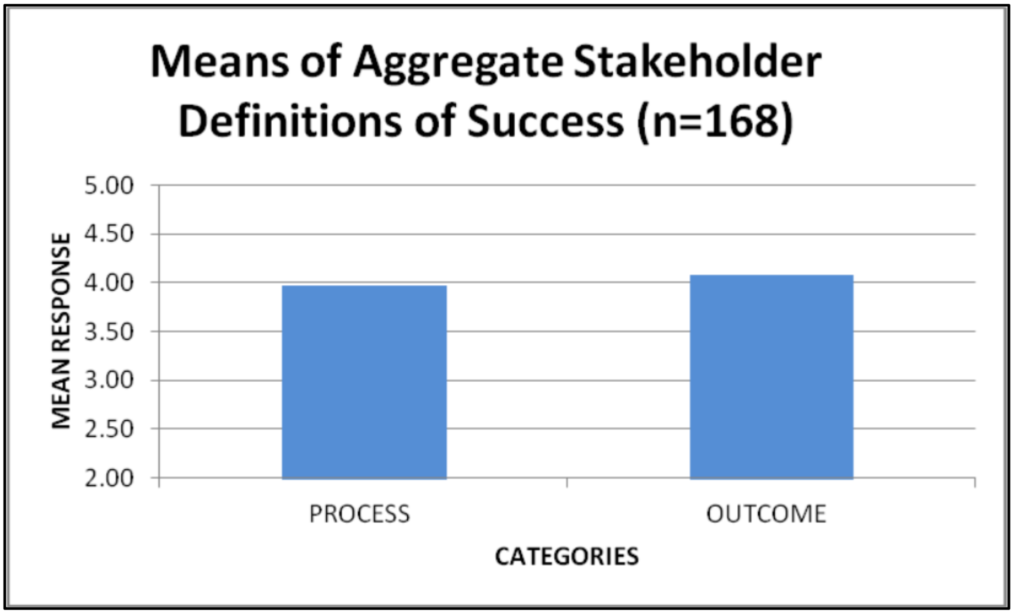

Figure 3. Means of Aggregate Stakeholder Definitions of Success

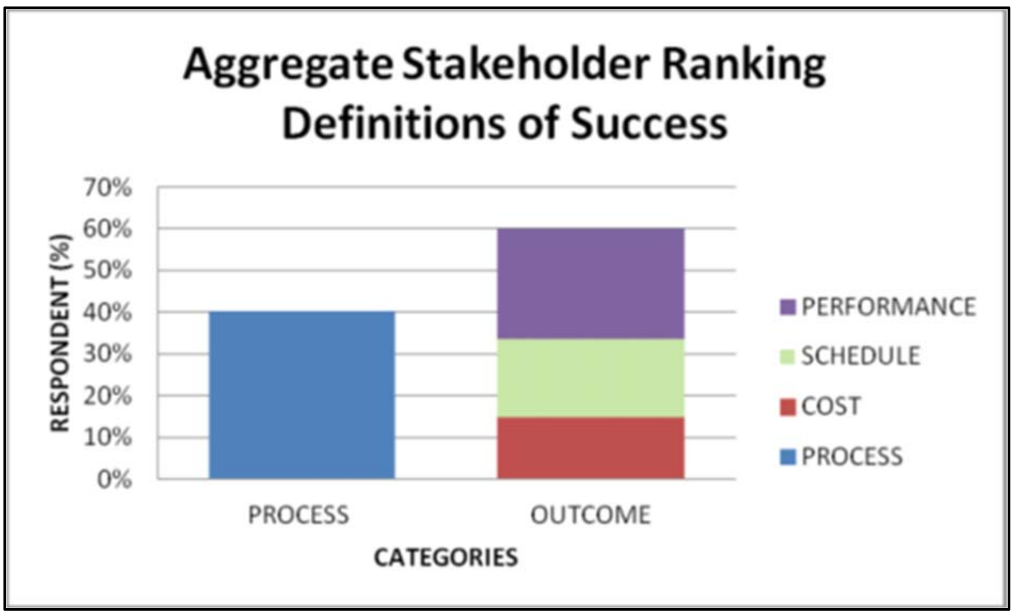

Figure 4. Aggregate Stakeholder Ranking of Definitions of Success

Measuring the Success of a Service Contract

Our survey also requested that participants rate on the Likert scale the various degrees of importance, and the extent to which they agreed or disagreed with, various factors when considering how they measure the success of a service contract. Again, these factors related to either processes or outcomes. The overall Likert scale mean with relation to processes was 2.48, and the outcomes displayed an overall mean of 3.71. Clearly outcomes are deemed more important by our participants as a whole. Our findings are displayed graphically in Figure 5.

If we look at the distinct factors within outcome of cost, schedule, and performance, the overall Likert means were 3.96, 3.84, and 3.30, respectively.

One hundred and sixty-eight respondents were asked to rank different factors related to measuring the success of a service contract. Of the 168 respondents, 46% felt that process-related factors were the most important. Fifty-four percent felt that outcome-related factors were the most important. The distribution of highest ranked responses is displayed in Figure 6.

Breaking down the outcome-related factors further, 19% of respondents felt that cost-related factors were the most important, 12% felt that schedule-related factors were most important, and 23% felt that performance-related factors were most important.

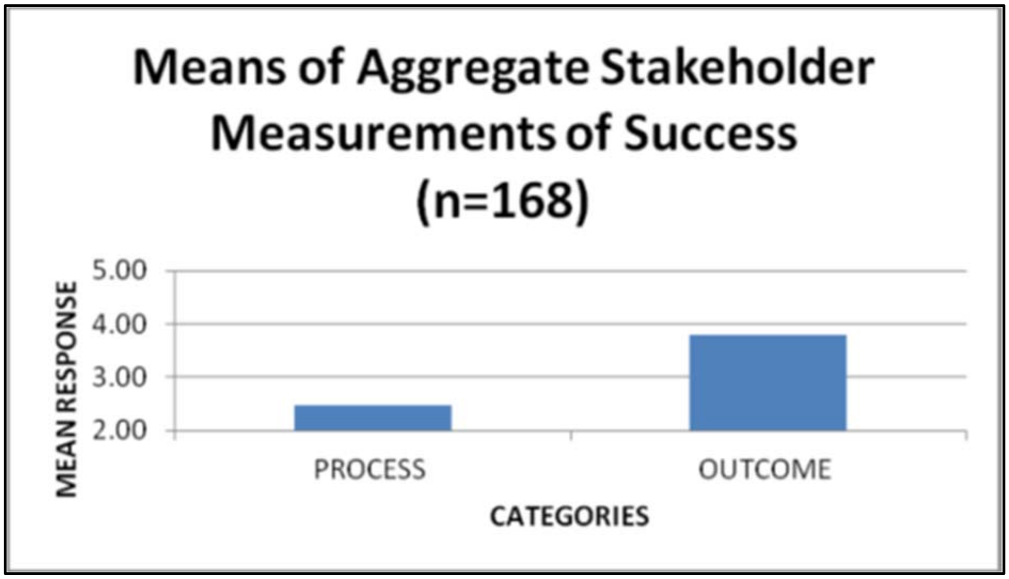

Figure 5. Means of Aggregate Stakeholder Measurements of Success

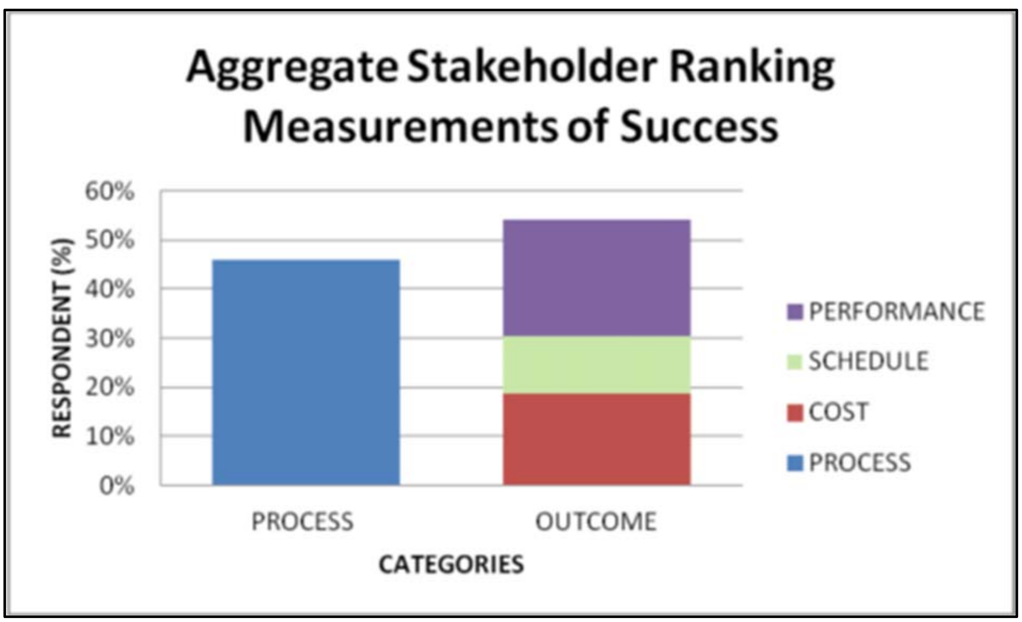

Figure 6. Aggregate Stakeholder Ranking of Measurements of Success

Analysis of Aggregate Survey Data

The findings from the analysis of aggregate survey data show that when asked to respond on a Likert scale, different stakeholders find all aspects of processes and outcomes important when defining the success of a service contract. The means of the responses we collected are very close, and it does not seem that, as a whole, our population favors process or outcome when defining success. Perhaps this is due to the nature of Likert scale questions. When asked if something such as cost overruns, major milestones, or a lack of protests is important, all stakeholders will invariably say yes. That is why the overall mean of all responses, for both outcomes and processes, is fairly high at 4.03. When forced to rank, the responses differ and outcome-related responses received a high rank of 1 or 2 60% of the time. This is because outcomes such as keeping on schedule and budget adherence are easy to understand and define. Process-related factors such as administration and communication are relatively harder to quantify.

The findings also demonstrate that when measuring the success of a service contract, all stakeholders tend to focus on outcomes and do not take into consideration the processes; this was true for both Likert-scale responses and ranking responses. This is very evident in the Likert-scale responses, where none of the process-related factors showed a mean of 3 or more. When forced to rank the different factors with respect to measuring success, the results were similar to defining success, with 56% of "most important" responses falling under the outcomes category.

In general our findings from the "other" category mirrored our aggregate results. Although there were only 10 responses, all felt that outcomes were the most important factor when defining and measuring the success of a service contract. We found that our stakeholders in this category rated and ranked processes extremely low in both defining and measuring the success of a service contract. This is because these stakeholders are not terribly burdened by administration and other process-related factors, so they feel that these factors are not important. For example, a contractor or end user does not necessarily conduct market research or choose the appropriate contract type. However, they are very concerned with staying within cost, keeping up with schedule, and maintaining a high level of performance.

Survey Results: Stakeholder-Level Data

As a starting point in examining how different stakeholders define and measure the success of a service contract, we performed a statistical analysis of the data to determine whether there were significant differences between the ratings on the Likert scale across the major stakeholders. We first performed an *F*-test for sample variances to determine the appropriate *t*-test to perform. In all instances, we found that there was an equal variance among stakeholders. The only statistically significant difference was between the CORs and COs/specialists when measuring success. This could be due to the fact that CORs view communication and other processes as key factors when measuring the success of a service contract. The COR is also likely to view a protest as a serious issue when measuring success because it results in a delay of execution and CORs cannot perform their duties. Otherwise, there was no statistically significant difference between any other of the stakeholders on the Likert scale. We discuss in the next section the results of the analysis of stakeholder-level data.

Analysis of Stakeholder-Level Data

Consistent with the abovementioned results of statistical analysis, we found that PMs, CORs, COs, and contract specialists all agree that outcome is slightly more important than processes based on participants' ratings of separate factors on a Likert scale. Each

functional role rated outcome slightly over 4.00, while rating processes just below 4.00. The mean of the functional roles combined was 3.94 for processes, and 4.11 for outcomes. Within outcome, performance-related factors received the highest average rating, while schedule-related factors received the lowest average rating. All functional roles showed an upward trend from schedule, to cost, to performance. A comparison of our Likert scale findings for defining success across functional roles is displayed graphically in Figure 7.

When stakeholders were asked to rank different factors concerning their definition of success, we found that there was clear agreement that outcomes are more important than processes. There was, however, some disagreement within the outcome factors of cost, schedule, and performance. CORs felt that cost was the most important factor, while PMs, COs, and specialists placed performance at the top of their rankings. Examined collectively, the major stakeholders provided 168 responses when ranking their definition of the success of a service contract. Sixty percent of respondents felt that outcome-related factors were most important, while 40% felt that process-related factors were the most important when defining success. The distribution of highest ranked responses is displayed in Figure 8.

Figure 7. Definitions of Success Across Major Stakeholders

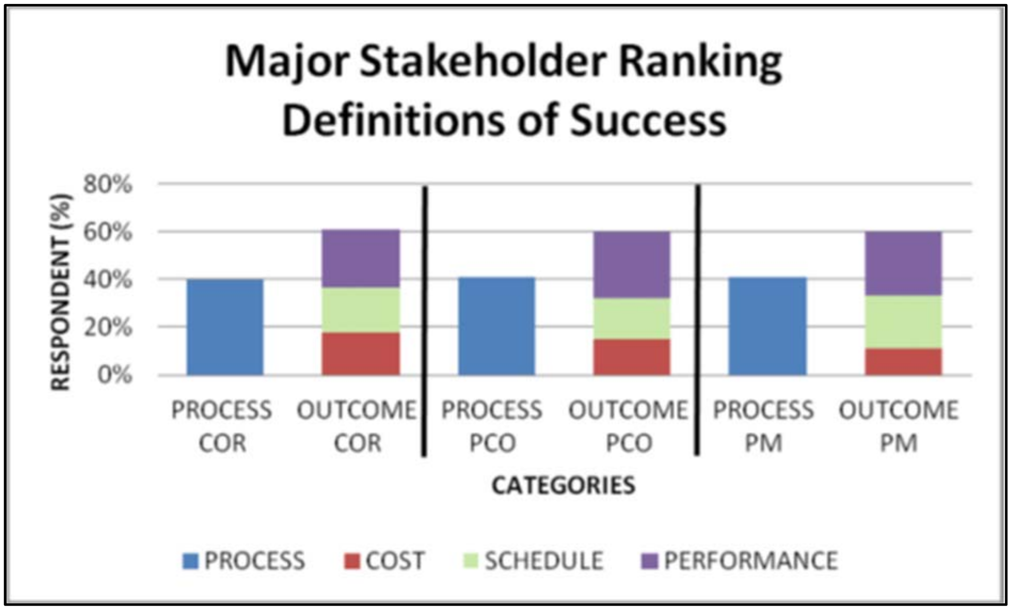

Figure 8. Major Stakeholder Ranking of Definitions of Success

According to the survey data, stakeholders also tend to measure success in almost the same way. When asked to rate different factors on the Likert scale related to stakeholders' measures of success, all respondents agreed that outcomes far outweigh processes. When looking at the mean across stakeholders, processes received a rating of 2.56, while outcomes received a rating of 3.78. Within outcome-related factors, stakeholders showed an upward trend from performance, to schedule, to cost. A comparison of our findings for defining success on the Likert scale across functional roles is displayed graphically in Figure 9.

Our ranking data shows that, again, major stakeholders prefer outcome-related factors when measuring the success of service contracts. When examined in aggregate, the major stakeholders provided 168 responses to our ranking questions. Of these responses, 43% of respondents felt process factors were most important, while 57% were in favor of factors related to outcomes. The distribution of highest ranked responses is displayed in Figure 10.

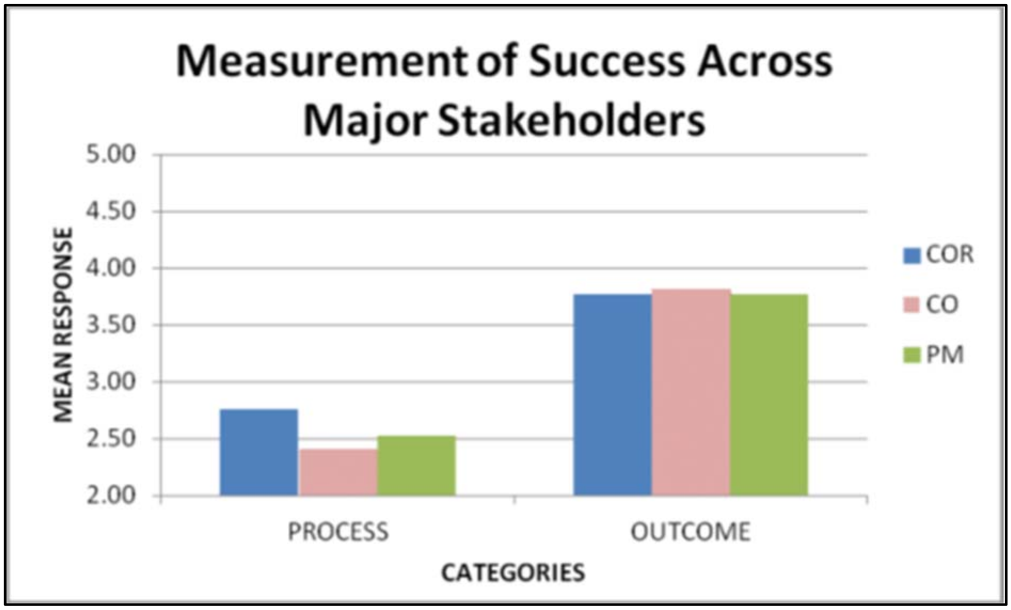

Figure 9. Measurement of Success Across Major Stakeholders

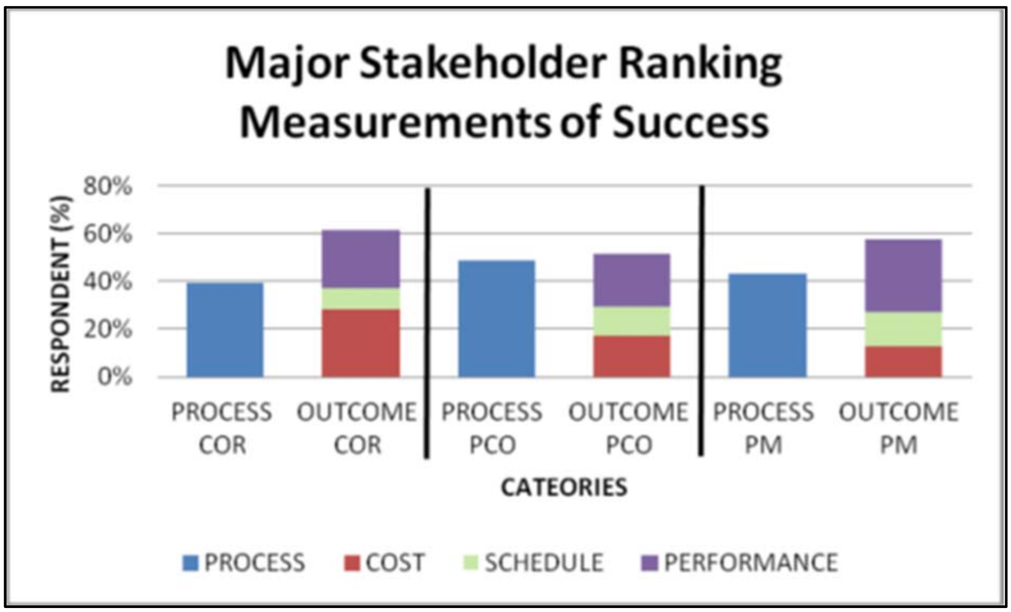

Figure 10. Major Stakeholder Ranking of Measurements of Success

The Likert scale responses for definitions of success were, again, relatively high, and this was due to the reason explained earlier. It is interesting that in both defining and measuring success, CORs ranked cost highest out of the three stakeholders.

Another interesting result is that COs tended to place nearly equal importance on process and outcomes when forced to rank factors concerning measuring success. This is probably due to the administrative nature of the COs' role. For example, their functional role has to deal with modifications, COR reports, and exercising options. The other functional roles of PMs and CORs are not overly concerned with processes and are focused on the requirement and outcomes. The data reflect this fact.

It is interesting to note that every demographic consistently rated processes significantly higher on the Likert scale when defining success versus measuring success. We feel that this is because stakeholders view measures as a tangible entity associated with post-award functions. Measures such as cost, schedule, and performance are fairly straightforward inasmuch as a goal is either met or not. Processes such as communication flow and overall management are more obscure and subjective. The stakeholders rated processes higher for defining success because they are closely associated with mainly pre-award functions. Processes such as choosing the correct contract type and appropriately evaluating the proposal are crucial for success. Because these are pre-award activities, it is easier to define success rather than measure it.

Summary, Conclusions, and Recommendations

Summary

The DoD's obligations on contracts have more than doubled between fiscal years 2001 and 2008 to over $387 billion, with over $200 billion spent just for services in 2008 (GAO, 2009). In conjunction with this increase in defense procurement is the reduction of the defense acquisition workforce. The combination of the increasing defense procurement workload and the decreasing size of the government workforce, along with the complexities of an arcane and convoluted government contracting process, have created the perfect storm—an environment in which complying with government contracting policies and adopting contract management best practices has not always been feasible (Rendon, 2010). The contract management process is performed with inputs from the different functional areas, using a cross-functional team or integrated project team (IPT) structure. Each of these project team members represents the stakeholders, and their different goals and objectives. The first research question we investigated was as follows: How do different stakeholders *define* successful services contracts within the Navy? To develop a clear understanding of current services acquisition practices, we also investigated a second research question: How do different stakeholders *measure* services contracts within the Navy? Investigating the above two questions helped us develop recommendations regarding the third and final research question: How should the service contract's success be measured?

Conclusions

On the aggregate level, our research indicated that, when defining a successful service contract, stakeholders considered outcomes (in the order of performance, cost, and schedule) slightly more important than processes. Stakeholders also ranked outcome-related factors as most important. On the aggregate, our research indicated that, when measuring a successful service contract, stakeholders considered outcomes (in the order of cost, schedule, and performance) more important than processes. Stakeholders also ranked outcome-related factors as most important.

On the stakeholder level, our research indicated that, when defining a successful service contract, PMs, CORs, and COs considered outcomes (in the order of performance, cost, and schedule) slightly more important than processes. PMs, CORs, and COs also ranked outcome-related factors as most important. On the stakeholder level, our research indicated that, when measuring a successful service contract, PMs, CORs, and COs considered outcomes (in the order of performance, schedule, and cost) more important than processes. PMs, CORs, and COs also ranked outcome-related factors as most important.

Recommendations

Our research findings have several implications for the Navy, as well as the DoD. All stakeholders surveyed identified and ranked outcome-related factors as more important

than process-related factors, in both defining and measuring the success of service contracts. This may be because outcome-related factors (cost, schedule, and performance) are more easily defined and measured using available metrics, compared to contracting processes, which are more difficult to define, and many agencies have no available metrics. However, as discussed in the earlier sections of this paper, many of the contracting deficiencies identified by the GAO and DoDIG are related to contracting processes, such as conducting market research, determining item commerciality, selecting contract type, negotiating fair and reasonable prices, and monitoring contractors through surveillance. Thus, our first recommendation is that the U.S. Navy develop and implement process-related metrics to define and measure critical contracting processes, such as conducting market research, determining item commerciality, selecting contract type, negotiating fair and reasonable prices, and monitoring contractors.

Our literature review identified that acquisition stakeholders (PMs, CORs, and COs) have different procurement goals and objectives, and these goals and objectives may in fact conflict with each other. Our second recommendation is that the U.S. Navy should establish internal controls to ensure the contracting processes are being followed and that the different stakeholders place sufficient importance on the value of these contracting processes.

Finally, as previous research has determined that contracts are only as successful as the processes used to plan, award, and administer these contracts, our final recommendation is for the U.S. Navy to implement a program for continuously assessing its contracting process capability and using the assessment results to improve its organizational contract management process capability. Once the U.S. Navy, as well as the DoD, implement contracting process-related metrics to define and measure services contracts, internal controls to ensure contracting process compliance, and periodical assessments of organizational contracting process capability, the importance of process-related factors in defining and measuring the success of service contracts will increase among stakeholders and thus start addressing some of the contracting deficiencies identified by the GAO and the DoDIG.

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Make or Buy: A Systematic Approach to Department of Defense Sourcing Decisions for Services (An Interim Report)

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Abstract

Over the last decade, Department of Defense (DoD) spending on service contracts more than doubled in constant terms, from $90 billion in 2000 to $183 billion in 2012. Policy makers have recently attempted to reduce or even reverse this trend, in part by emphasizing instead the “in-sourcing” of work performed under services contracts. Over the last three years, the Center for Strategic and International Studies (CSIS) has worked to develop a more systematic framework for guiding sourcing decisions for services contracts within the DoD, which would have broader implications for the whole universe of budget-based decisions within the DoD. Towards that purpose, this paper analyzes the stated motivations, implementation strategies, and guiding analytical underpinnings for previous outsourcing efforts and for the currently ongoing in-sourcing initiative. It then assesses current and previous DoD methodologies for guiding sourcing decisions, highlighting the individual strengths and shortcomings of these methodologies. The third section of this paper analyzes

public sector sourcing decisions in the wider context of economics and business management, to provide broader conceptual insights for more informed determinations on these sourcing decisions. All of this research is being used to develop a repeatable, verifiable, data-driven methodology to guide sourcing decisions, which will be presented in the final report of this project.

Introduction

Over the last decade, Department of Defense (DoD) spending on service contracts more than doubled in constant terms, from $90 billion in 2000 to $183 billion in 2012.[1] Policy makers have recently attempted to reduce or even reverse this trend, in part by emphasizing instead the "in-sourcing" of services contracts. In the past, conversions from government civilians to contractors have been done for reasons of policy or projected cost savings. More recently, conversions from contractors to government civilians, as well as other actions to expand the federal workforce, have been undertaken for a similar combination of policy reasons and projected cost savings. Weaknesses in the methodology used by the DoD to justify or budget for in-sourcing decisions call into question whether the DoD is using accurate data on the cost implications of its sourcing decisions.

Over the last three years, the Center for Strategic and International Studies (CSIS) has worked to develop a more systematic framework for guiding sourcing decisions for services contracts within the DoD. This framework also has broader implications for all budget-based decisions within the DoD. Towards that purpose, this paper first analyzes the stated motivations, implementation strategies, and guiding analytical underpinnings for previous outsourcing efforts and for the currently ongoing in-sourcing initiative. It then assesses current and previous DoD methodologies for guiding sourcing decisions, highlighting the individual strengths and shortcomings of these methodologies. The third section of this paper analyzes public sector sourcing decisions in the wider context of economics and business management, to provide broader conceptual insights for more informed sourcing decisions. All of this research is being designed to support the development of a repeatable, verifiable, data-driven methodology to guide sourcing decisions, which will be presented in the final report of this project.

Department of Defense Sourcing Policy

Office of Management and Budget (OMB) Circular A-76

OMB Circular A-76 was the result of over three decades of policy deliberation towards ensuring that the government did not improperly compete with private enterprise. Starting in the 1930s, a series of commissions and reports grappled with the problem of what tasks should (or must) be performed by government employees, and what tasks are better left to the private sector. These debates culminated during the 1950s and 1960s in the issuing of guidance documents that ultimately became Circular A-76 (hereafter referred to as "A-76"), which sought to lay out uniform guidance on sourcing policy across the federal government[2] (Halchin, 2007, pp. 3–4).

A-76 has been revised several times since its issuance, but the core of the guidance has always been the competitive process, better known as public–private competition. A-76 has never mandated competition for any particular function (though two administrations, those of Presidents Ronald Reagan and George W. Bush, issued policies setting targets for

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[1] Federal Procurement Data System (FPDS.gov) data with CSIS analysis.
[2] The most recent revision of Circular A-76, issued in 2003, can be viewed here: http://www.whitehouse.gov/sites/default/files/omb/assets/omb/circulars/a076/a76_incl_tech_correction.pdf

numbers of positions to be competed); rather, A-76 laid out procedures for how such public–private competitions were to be conducted (Halchin, 2007, p. 6). The competitive process included three broad steps, once a function had been identified for competition:

1. issuance of a Performance Work Statement, to lay out clearly the tasks to be performed and ensure that competitors were "bidding" for the same work;
2. formation of a Most Efficient Organization (MEO) within the government to serve as the government's offeror; and
3. selection of a private competitor from the field of bidders, to compare against the government option.

After adjustments to compensate for differences in projected performance levels, to ensure balanced and fair cost comparisons, if the private bid were 10% or $10 million less than the government option, the function would be outsourced (Commercial Activities Panel [CAP], 2002, p. 19).

OMB Circular A-76 Within the DoD

From the start, the DoD has been the most active agency in performing A-76 cost comparisons. After increasing sharply in the late 1970s and early 1980s, A-76 competitions within the DoD declined by over half in the latter half of the 1980s, a trend which continued into the early- to mid-1990s, when very few competitions were started (Keating, 1997, p. 4). Competitions started to increase in the late 1990s and early 2000s, but between 1997 and 2001, there were fewer cost comparisons performed, combined, than in any individual year in the early 1980s (CAP, 2002, p. 21). In the late 1990s and early 2000s, A-76 was one part of the DoD's comprehensive "strategic sourcing" initiatives, designed to cover the whole range of DoD activities (GAO, 2000, p. 3). Historically, the Navy (which has conducted the most competitions) and Air Force have had the most active A-76 cost-comparison programs, with the Army conducting about a third fewer competitions than the Navy, and the USMC and various DoD agencies each accounting for less than a sixth of the total number of competitions started by the Navy (Keating, 1997, p. 7).

Numerous studies have shown that the A-76 competitions have produced significant savings, more as a result of competitive pressures than any inherent advantage of public or private providers (Tighe et al., 1996, p. 11). The government MEOs and industry each won approximately half of the competitions, on average (Keating, 1997, p. 18). A review of several studies on savings produced through A-76 competitions showed an average savings of around 30% across a number of different functions and tasks, though that number was highly variable (ranging from 15% to 45%). One study noted that the highest savings were achieved when military billets were converted, though there are limits to which military functions can be classified as "commercial" or not inherently governmental.

Criticisms and Problems With A-76 Implementation

In reviewing the literature, the majority of technical criticisms of the A-76 process focus not on the policy itself but rather on the implementation of the competitions. One particularly troubling figure is seen in a RAND review of DoD A-76 cost comparisons: For every 13 cost comparisons started in the period reviewed, five were cancelled (Keating, 1997, p. 9). These cancellations happened for a number of reasons, though large delays in soliciting and preparing bids seemed to be a common cause, and studies of large functions were at greater risk of being cancelled before completion. A provision in the fiscal year (FY) 1991 DoD Appropriations Act imposing a 24-month limit on single-function cost comparisons going forward also influenced the rate of cancellations (Keating, 1997, p. x). The length of time for competitions to be completed was a recurring problem cited in the literature;

according to the aforementioned RAND study, the median time for completion was 664 days, with a mean of 810 days (Keating, 1997, p. 35). In discussions with stakeholders, the long delays were seen as troublesome by both industry and government sources, due to morale issues caused by uncertainty regarding job security (on the government side) and the inability to plan revenues and workload (on the industry side.)

The lack of post-decision follow-up on A-76 competitions was another major source of criticism. Despite some mechanisms in place, there was no consistent effort within the DoD to track whether A-76 competitions produced projected savings or met promised performance levels (GAO, 2002, p. 4). Another major area of criticism was with how A-76 was being used. The 2002 Commercial Activities Panel report evaluating government sourcing policy noted that, while A-76 functioned reasonably well as a way to compare the cost of government and private performance, it was being stretched to include evaluations of other factors it was never designed to weigh: “quality, innovation, flexibility, and reliability” (CAP, 2002, pp. 10, 41–43).

Moratorium

In January 2008, Congress passed legislation suspending A-76 cost competitions within the DoD (and throughout the rest of the government in March 2009), a prohibition which has been consistently renewed in the years since then. Attached to legislation continuing the prohibitions in 2010 and 2011 were calls for studies of A-76 to be completed by various stakeholders, including the DoD Inspector General (DoDIG) and the Government Accountability Office (GAO), which would be used to determine whether A-76 competitions would be allowed to resume. Although all required studies have been delivered to Congress, and many of them recommend resuming A-76 competitions, neither Congress nor the current administration have acted to revive A-76. In fact, the President’s FY2013 budget request includes a provision explicitly prohibiting funds from being used for any outsourcing-related study or competition (Bailey Grasso, 2013, pp. 5–8).

The DoD’s In-Sourcing Initiative

On April 6, 2009, Secretary of Defense Robert M. Gates announced a plan to reduce the DoD’s reliance on contractors and expand its use of federal civilians to provide services (Gates, 2009). Between 2010 and 2015, this in-sourcing initiative projected the replacement of more than 30,000 contractors with DoD civilians. According to Gates’ announcement, this would “restore balance” to the workforce by returning the ratio of contractors to DoD civilians to its 2001 level. A plain reading of contemporaneous budget documents indicates that the plan was also based on an assumption that federal civilians would be significantly less costly than the contractors they replaced. As a result, the DoD planned to achieve budgetary savings equal to 40% of the cost of the contractors being replaced; more recent DoD statements claimed savings of 25% (Gates, 2010). Neither figure appears justifiable—research has shown that the about 65% any savings achieved through public–private competitions derive from the competition itself, not from any intrinsic advantage on either the public or private side.[3] The FY2010 DoD budget reflected those savings, as have subsequent DoD budget proposals to Congress.

This initiative was consistent with a variety of other legislative and policy decisions on the role of government contractors. The National Defense Authorization Acts (NDAAs) of 2006 and 2008 required the DoD to consider greater use of federal civilians. A March 4, 2009, Presidential Memorandum on government contracting required the OMB to review

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[3] See, for example, Snyder, Trost, and Trunkey (1998) and Trunkey, Trost, and Snyder (1996).

policies for contracting for services (Obama, 2009). Numerous GAO and DoD IG reports have cited the DoD's over-reliance on contractors.[4]

A DoD report to Congress in December 2009 indicated that 17,000 additional civilian positions would be established in 2010 as the result of new in-sourcing efforts (McGinn, 2009, p. 6). Of this 17,000, half are for commercial activities, which the report states can be done at lower cost in-house. Another 42% are for commercial activities that the DoD would exempt from private sector performance on the grounds that they support readiness or workforce management needs, including the need to provide for career progression and for the "oversight and control of functions closely associated with inherently governmental work" (McGinn, 2009, p. 5). The remaining 8% is for work that the DoD has determined is inherently governmental. The reliance on cost analysis for half of the in-sourcing goals clearly puts a burden on the DoD using proper taxonomies and methodologies to compare the cost of government employees and contractors (McGinn, 2009, pp. 4–5).

The December 2009 DoD report included a number of changes from the plans announced in April 2009. One significant change was to expand the types of services affected by the initiative. The original plan focused on two budget categories—advisory assistance services and the category called "other services." However, that plan was expanded to allow managers to consider any type of contracted service for in-sourcing, including activities such as laundry services, installation maintenance, and transportation. Targeting these expanded activities for in-sourcing is only consistent with previous policy directives if cost savings can be realized. CSIS concluded at the time that the process was insufficient to validate those savings and that there were sound reasons to suspect they would not be achieved (Berteau et al., 2011, pp. 5–7).

In an August 9, 2010, statement, Secretary of Defense Gates himself de-emphasized in-sourcing, signaling that expected savings were not materializing. Subsequent statements from DoD officials have stated that existing in-sourcing initiatives by the military departments remain in full force, however (Brodsky, 2010). In the course of this research effort, discussions with DoD officials have indicated that the expected savings from in-sourcing are still built into budgets, and some within the DoD still believe that in-sourcing, in and of itself, will lead directly to large savings. The Ike Skelton National Defense Authorization Act for Fiscal Year 2011 mandates that the "Secretary of Defense shall use the costing methodology outlined in the Directive-Type Memorandum 09–007 (Estimating and Comparing the Full Costs of Civilian and Military Manpower and Contractor Support) or any successor guidance for the determination of costs when costs are the sole basis for the decision."

Recent legislative action and statements from the DoD do show a weakening of support for in-sourcing. Secretary of the Army John McHugh suspended all of the Army's in-sourcing activities through a February 1, 2011, memorandum on "Reservation of In-Sourcing Approval Authority." More recently, section 937 of H.R. 1540, the House version of the FY2012 National Defense Authorization Act, called for an end to the temporary moratorium on public–private competitions that was established in the FY2010 NDAA. Though this provision did not make it into the final bill, it does signal a shift in Congressional support away from in-sourcing.

The release of the Office of Federal Procurement Policy's Policy Letter 11-01, released on September 12, 2011, marks the most recent major policy development relating to the broader issue of sourcing decisions. This guidance provides a much-needed

[4] See, for example, GAO (2006) and DoD Inspector General (2009).

framework for sourcing decisions based on three categories of work: inherently governmental, closely associated, and critical classifications. While this guidance represents a welcome step in the right direction towards clarifying the standards for declaring positions or functions inherently governmental or closely associated, various stakeholders have expressed a desire for more specific guidance going forward to help eliminate uncertainty regarding the boundaries of those categories, and the guidance for "critical classifications" has also been called ambiguous and imprecise.

DoD Cost-Estimation Methodologies

Given that the focus of DoD sourcing policy has been on issues of cost, the soundness of the cost-estimation methodologies at the heart of those policies is crucial. As CSIS has noted in previous work on the subject, however, having a repeatable, verifiable, data-driven cost-estimation methodology for calculating the cost of government performance is critical even outside the realm of sourcing policy. Particularly in times of budgetary strain such as exist today, the DoD will be making decisions about the future of programs and functions based on perceived potential cost savings. Without a rigorous cost-estimating methodology to determine the fully burdened cost of a particular function to the government as a whole (or even simply to the department), the DoD lacks a process to gather, verify, and use the data it needs to make such decisions, without which it will not know the true cost implications of the decisions it makes.

Since 2009, the cost-estimating methodology of DTM 09-007 has replaced the methodology from A-76 as the standard for use within the DoD. As has been explored in previous work by CSIS on the subject, this change did not represent an improvement (Berteau et al., 2011, pp. 9–11).

Directive-Type Memorandum 09-007

In-sourcing decisions made on the basis of cost depend on the ability to project accurately the relative costs of the governmental and private options. Further, even if in-sourcing is done for policy reasons (such as rebuilding the DoD acquisition work force), the DoD still needs to know the cost impact of these actions. Without these data, any cost comparison is no more than guesswork. In part to meet those objectives, on January 29, 2010, the Director of the Cost Analysis and Program Evaluation (CAPE) signed Directive-Type Memorandum (DTM) 09-007, "Estimating and Comparing the Full Costs of Civilian and Military Manpower and Contract Support." This DTM constitutes current DoD guidance for in-sourcing decisions, and the NDAA for Fiscal Year 2011 mandates that the

> Secretary of Defense shall use the costing methodology outlined in the Directive-Type Memorandum 09–007 (Estimating and Comparing the Full Costs of Civilian and Military Manpower and Contractor Support) or any successor guidance for the determination of costs when costs are the sole basis for the decision.

Yet the procedures laid out in the DTM for calculating the government's costs for performing a service have several significant gaps. These gaps raise questions about the validity of any analysis generated on the basis of DTM guidance. The DTM is written to encourage analysts to "carefully consider" all possible costs associated with contracts, but the guidance itself overlooks many cost aspects for the government side. Among other shortfalls, the DTM

- Lacks the ability to calculate fully burdened government-wide costs. The DTM states that "manpower cost estimates normally address costs to the Department of Defense," and that "the costs of service contracts are variable

costs in the short run paid by the Department of Defense." Analysts have interpreted the lack of consistent focus on fully burdened government-wide costs to mean they could leave out costs or savings that accrue not to the DoD but to other federal agencies.

- Creates a gap by failing to account for the full cost of DoD-owned capital while requiring the inclusion of those costs for contractors. This ignores the fact that the real economic costs of capital devoted to risky commercial activities—including forgone interest and a risk premium as well as depreciation—are present regardless of whether the activity is performed by a public or private producer. The failure to consider any capital costs for government workers is a step backwards from the costing approach used under OMB Circular A-76 (see the following section), which included the cost of in-house production at a private sector rate of return on new investments. It is difficult to determine the federal cost of capital, but there is universal agreement that the cost is not zero.
- Fails to account for taxes forgone by the federal treasury or state or local governments. This is another step back from OMB Circular A-76, whose costing methodology included forgone federal taxes as a cost element for in-house producers.
- Fails to account for the inherent risk of cost growth among public producers. The available empirical evidence indicates that, for competed workloads, subsequent cost growth depends on changes in the size and scope of work, not on which sector wins. The DTM approach effectively eliminates competition, and history says the absence of competition will cause cost to increase over time.
- Overlooks the cumulative cost effect of multiple in-sourcing decisions. Indirect costs such as the cost of payroll processing or of day-care centers do not increase as the result of any single in-sourcing decision, but those costs will likely rise as the result of the cumulative effect of a systematic in-sourcing initiative.
- Overlooks the imputed costs of insuring and indemnifying in-house producers. OMB Circular A-76 methodology correctly required that in-house producers take into account what it would cost if they were required to purchase casualty and liability insurance. In contrast, the DTM recognizes the costs of insurance and indemnification to private producers, but there is no mechanism in the DTM that attributes such costs to public producers.[5]
- Fails to account for varying workload stability. Some tasks require a rather constant allocation of human resources, while others experience high levels of volatility. While this is not a cost factor per se, the flexibility of contractors can provide an advantage to the government when workload is variable, and the lack of flexibility in the government means there is a cost to maintaining an unneeded workforce in that case.
- Should require a detailed scope of work as a better basis for cost estimation. Such a detailed scope of work was required as a basis for cost estimation by

[5] Note that although the government does not buy insurance, it implicitly insures its in-house producers. The cost of purchasing insurance reflects the expected amount of these costs.

the A-76 process, which referred to that scope of work as a Performance Work Statement. Without a scope of work that accurately lays out the requirements of the task to be performed, it is impossible to ensure that the full cost of performance is captured in any cost estimate.

If the true cost of public performance of commercial services cannot be determined, any budget-driven decision becomes immediately suspect, whether the decision is to insource work currently done by a contractor or simply to change the size of a specific part of the government workforce. Such a situation gives rise to questions like "How can the DoD claim it is saving 40%, or 25%, or any specific amount via in-sourcing private-sector positions if it doesn't know how much the newly insourced function will cost?" and "How can the Office of Management and Budget approve a new government activity if it does not know the full cost impact on current and future budgets?" The DoD and the federal government should understand the full budgetary implications of every personnel decision so that it can properly weigh the benefit gained (such as improving in-house capabilities) against the budgetary impact.

OMB Circular A-76

OMB Circular A-76 provided the previous cost comparison methodology used by the DoD. Given the flaws of the DTM, it is worth considering how well the A-76 provides a basis for addressing those flaws and performing better cost estimates of government performance. As previously discussed, there were numerous problems with the implementation of A-76 cost competitions. In discussions with experts, however, there was broad agreement that, aside from the two specific problems discussed below, the A-76 costing methodology did a reasonably good job of accurately capturing the major cost elements of government performance.[6] Based on CSIS analysis, the A-76 performs better than the DTM in the following respects:

- provides greater specificity on major cost components,
- includes the cost of in-house production at a private sector rate of return on new investments,
- includes forgone federal taxes as a cost element for in-house producers,
- requires that in-house producers take into account what it would cost if they were required to purchase casualty and liability insurance, and
- requires a Performance Work Statement.

Of these, the most important is the fact that the A-76 provides far greater specificity on major cost components, thus providing better guidance for cost estimators on how to compute more of the range of the fully burdened cost. In contrast, the DTM provides only general explanations of how to calculate many major cost elements (aside from direct labor costs).

At the same time, A-76 still exhibits flaws which must be recognized and corrected. In reviewing the literature regarding A-76, the majority of criticism relates to the competition process itself or to the lack of follow-up after a public-sector victory to ensure performance,

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[6] It should be noted that, while the experts CSIS spoke to for this study agreed that the A-76 cost-estimating methodology captured most of the major cost elements, there was also broad agreement that there were serious weaknesses in the quality of the data the DoD used to calculate the totals for those cost elements.

rather than flaws in the cost-estimation methodology. Two major criticisms of the cost-estimation system itself do merit discussion, however:

- A-76 utilizes a blanket 12% overhead rate for all government functions. In discussion with stakeholders on both sides of the sourcing policy debate, as well as with former policy makers involved in A-76 drafting and implementation, there was agreement that the 12% overhead rate lacks any sound methodological basis, and that it was wholly inappropriate to have one overhead rate to cover all the disparate activities performed by the government. Industry representatives noted that private sector functions with extremely minimal overhead requirements had overhead rates two to three times higher. GAO has stated that the 12% figure came not as the result of a rigorous study of government overhead costs, but as a compromise between the government and the private sector (GAO, 1998, p. 5).
- A-76 fails to account sufficiently for the true cost of capital on the public side. A-76 is better in this respect than the DTM, which includes no accounting for cost of capital while forcing contractors to account for it in their pricing, but further research is needed to generate a methodology for fully capturing public-sector cost of capital.

Current Policy

Within the DoD, DoD 09-007 is still the relevant guidance methodology for sourcing policy and cost estimation. In discussions with policy makers, however, CSIS was unable to identify a single office or function that was utilizing the DTM cost-estimation methodology. Rather, each office and function uses whatever cost-estimation system they see fit, which has led to situations in which more than one function was assuming 0% overhead rates in calculating its own costs. The DTM was supposed to have been replaced with a more permanent DoD Instruction by September 2011, but that deadline has long since passed, and the revised deadline of April 1, 2013, was extended to August 2013. Indications are that the DoD Instruction will be issued no later than May 2013. In addition, the model that the DoD developed to aid in implementing the DTM will soon be available for use throughout the DoD. Also, the GAO is preparing a report for Congress on DoD guidance and compliance. The release date for this GAO report is not yet publicly available. CSIS cannot determine at this time the extent to which the DTM shortcomings cited above have been addressed in the Instruction or the degree to which the GAO will agree with those shortcomings. CSIS will update this section in the final report as further information becomes available.

Government-wide action on workforce costing also is continuing. On March 1, 2013, the Office of Federal Procurement Policy (OFPP) held a public hearing to gather information from stakeholders regarding sourcing and cost-estimation policy. According to the OFPP officials at the event, there is no impending rulemaking from the OFPP on either issue; rather, the OFPP recognizes that these are issues of concern to various stakeholders, and they are trying to “get smarter” on the issue in advance of any specific policy endeavor.

Lessons From Business Literature on Sourcing Policy

This section examines some of the relevant literature from the fields of economics and business management for insights that could help the DoD determine which services to produce in-house and which to purchase under contract or grant. The factors that private firms consider in making sourcing decisions have withstood the test of competition and may provide useful guidance. The section also considers findings from the literature on public bureaucratic behavior, as the intrinsic differences between governmental and private organizations may determine the ability to transfer findings from the private sector

experience to the government realm. Finally, it examines empirical studies that—without any theoretical preconceptions—compare the costs of in-house and contractor services or examine the outcome of competitions between DoD in-house providers and private sector contractors.[7]

One central and very clear finding that emerges is the correlation between competition and lower costs. For many DoD commercial activities, the cost reduction associated with competition is on the order of 20% to 40%.[8] Both the business and economics literature indicate that competition provides stronger incentives for cost reduction than do managerial initiatives that monitor performance or exhort efficiency.

The Make-or-Buy Decision in the Private Sector

Sourcing Decisions From an Economist's Perspective

Firms are sized and organized to maximize the value of output less both the costs of production *and the costs of the transactions* that must occur between the different players involved.[9] The literature identifies the costs of transactions and of information as important determinates of the extent to which firms will vertically integrate—and produce their own intermediate goods and services—as opposed to contracting for those goods and services from outside producers (Williamson & Winter, 1993). Transactions costs occur whenever goods or services transfer between a provider (the agent) and a user (the principal). The transactions costs associated with purchases of intermediate goods from outside suppliers include the costs of source selection, contract management, and monitoring. Those associated with in-house production include the costs of managing labor and the process of obtaining other needed inputs. Transactions between principals and the agents on whom they rely depend on governance mechanisms—including different types of contracts as well as incentives and performance monitoring. These mechanisms encourage the agents to pursue to goals of the principal.

The transactions costs associated with the use of outside providers are generally low for commercially available goods that can be purchased off the shelf and for generic commercial services that can be performed off-site—such as large-scale data entry. Accordingly, these are the kinds of goods and services that firms often choose to purchase rather than produce internally. The transactions costs associated with using outside producers are greater if the outside producer must invest in transaction-specific assets or skills that have few if any alternative uses (although long-term relationships between buyers and sellers—which in effect brings the workload closer to in-house—can help to alleviate this problem).

The basic findings of this literature are that, in the private sector, firms find that it can be cost effective to perform work in-house, rather than by contract, if:

- Flexibility is required to meet rapidly changing demands.

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[7] The focus of this section is on sourcing decisions for activities or functions, rather than on in-sourcing or outsourcing individual positions within activities. Because changes in sourcing typically change the quantity of labor used, a comparison of costs position by position is usually not relevant. The special situations which lead the DoD to contract for individual positions—including some that could be inherently governmental—are set aside for purposes of this section.

[8] The term *commercial* as used here does not mean a good or product that is readily available in the commercial sector; it means only that the activity is not inherently governmental and is similar to goods or services that are available in the private sector.

[9] See Simon (1991). For a nontechnical summary of the current literature, see Williamson & Winter, 1993.

- The quality or quantity of output is difficult to measure objectively.
- In-house workloads are large and steady enough to provide economies of scale.
- The work requires highly specialized human or capital assets.
- The market is not large enough to support competition among providers.
- The work requires personnel or facilities to be co-located with those of the buyer (site specificity).[10]

These factors explain, in part, why it can be more difficult to contract for services than for goods. Services must often be performed at the buyer's site to meet the unique requirements of his specific production process. They cannot be produced in advance and then sold to any willing buyer, and their quality and quantity may not lend themselves to a physical examination.[11]

Sourcing Decisions From a Business Management Perspective

The business management literature on sourcing decision, although consistent with the economics literature, identifies some additional factors that influence the make-or-buy decisions of private firms.[12] Since the 1990s, this literature has emphasized that a firm's competitive advantage often rests on excellence in a few (perhaps only two or three) "core competencies." Core competencies are defined as "the collective learning in the organization, especially how to coordinate diverse production skills and integrate multiple streams of techniques" (Prahalad & Hamel, 1990, p. 82). In effective organizations, core competencies are closely tied to the values of an organization and the identities of its managers and employees—identities which those values can help shape.[13] (This relationship is not limited to business. For example, in the military, the values of teamwork, loyalty, and honor reinforce the core competencies of combat units.)

The time and effort that senior managers can expend on non-core activities is limited. The support functions common to most producers, such as human resource management and inventory control, although essential to production, are often not among a firm's core competencies. They may not be closely monitored or controlled by the most senior managers and—if produced in-house—are not directly subject to market forces. In the absence of direct competition, in-house providers may fail to keep up with the standards—for quality and innovation as well as cost—that outside providers must meet. This literature suggests that non-core activities should be considered for outsourcing. In addition to any short-term reduction in the costs of obtaining the non-core good or service, outsourcing can

- free up management to focus on the core activities that drive the firm's competitive advantage,
- ensure access to the most cutting edge, world-class capabilities that could not be kept in-house cost effectively,
- shift risk to outside providers, and

[10] See Pint & Baldwin (1997) and Congressional Budget Office (1995).
[11] Many IT services may lend themselves to contracting because they do not need to be performed on site.
[12] This discussion of the business management literature draws on the work of Pint and Baldwin (1997).
[13] The importance of identity in motivating performance has recently been introduced into the economics literature (see Akerlof and Kranton, 2005).

- gain control over what could otherwise be an in-house monopoly.

The business literature gives less emphasis to the problems that firms encounter if their outsourcing decisions are poorly conceived or implemented. One author notes that strategic decisions to outsource can be misapplied by line managers who focus narrowly on short-run cost savings:

> While outsourcing may seem attractive at the strategic management level, serious pitfalls are often encountered as the strategy is pushed downward into operations. At the operational level, the strategic intent tends to be lost … implementation is in the hands of semiautonomous teams that are often tightly focused on measureable objectives—most often, cost reduction. Outsourcing at the operational level can easily lead to the development of dependencies that create unforeseen strategic vulnerabilities. (Insinga & Werle, 2000, p. 58)

Although the DoD has adopted some of the language of the business literature, it has not always adopted the spirit. For example, within the DoD, the need for direct command and control is often cited as a reason why specific support services should be kept in-house. This is consistent with military culture in which direct authority is very powerful. Yet the business literature indicates that senior managers in the private sector can often extract more control over an outside provider of non-core goods or services, who operates competitively, than they do over an in-house monopolistic provider (a provider over whom they have, at least nominally, direct authority; Stiglitz, 1991, pp. 15–24).

Another problem in applying the core concept is that it is difficult to distinguish core from non-core competencies. The DoD's core competencies would presumably include the application of military force in support of national security objectives as well as other inherently governmental functions—including the control of public funds and decision-making that commits the Department to an action. What else it might include is unclear. For example, the DoD uses the phrase "core workloads" to explain why some depot maintenance must be kept in-house. Yet this literature suggests that specialized workloads that cannot support competition or the need to maintain the expertise to be a successful buyer might be better justifications for some in-house capabilities.

Making Sourcing Decisions in the Private Sector

Both the economics and the business literature indicate that workloads can exhibit characteristics that make them appropriate for in-house production, while at the same time, other features might apparently qualify them for outsourcing. Firms must consequently balance the different characteristics of a workload when making sourcing decisions. This balancing process is not very transparent. The 2002 final report of the Commercial Activities Panel, a group chaired by David Walker of the GAO, notes that private sector managers typically review the merits of in-house as opposed to purchased goods and services at a strategic level inside the organization (CAP, 2002, p. 108). One of the panel's witnesses indicated that cost is the primary consideration in only a third of private sector sourcing decisions.

Direct bidding competitions between in-house and outside providers are very rare in the private sector; the Commercial Activities Panel was unable to identify any such competition. In contrast, it is not uncommon for private firms to maintain both in-house and outside providers for non-core goods or services. The in-house operations provide a base of expertise for evaluating the performance of the specialist providers and, if the market is thin, an alternative source of supply and a form of implicit competition (Pint & Baldwin, 1997, p. 9).

The Nature of Governmental Organizations and the Make-or-Buy Decision

Since the DoD is a governmental organization and not a private firm focused on maximizing profits in part by minimizing costs, its decisions on outsourcing will be driven at least in part by factors not considered in the business and economics literature. Indeed, the business literature fails to explain major features of the DoD's sourcing policies. For example, a key factor shaping a private firm's decision to choose in-house production for a good or service is the proximity to its core competencies and the competitiveness, or lack thereof, of the market. Yet a recent industrial review presented to the Defense Business Board concluded that the market for the services used by the DoD was generally highly competitive, while there was no competition for the production of aircraft carriers, tanks, and ICBMs. For many decades, the DoD has contracted for the production of weapons systems while sourcing policy has focused on contracting for services, therefore acting in direct contrast to practices in the private sector. While the lack of competition for major weapons systems has many causes, a look at the literature dealing with governmental agencies and bureaucratic behavior provides some additional insight into this sourcing practice.

Constraints and Objectives of Public Managers

Both the classical economics literature and the more recent work on the behavior of bureaucracies suggest that public producers might, in theory, be both less anxious and less able to minimize the costs of production than their private counterparts.

From a narrow perspective, the only intrinsic difference between a public producer and a private producer is that one is owned by the government and the other by private individuals. Accordingly, the economics literature asks whether a government-owned firm, operating in a competitive market without either constraints or subsidies (such as implicit loan guarantees), would be at an advantage or disadvantage relative to a private firm. The literature concludes that public production is at a disadvantage. The owners of the private firm can more readily sell their firm on the market at a price that reflects its future net earnings. The fact that the value of the investment can be immediately realized gives the private firm better investment incentives (Alchian & Demsetz, 1972, pp. 777–795).

The literature on government agencies and public bureaucracies approaches this question from a much broader perspective.[14] It emphasizes the fact that government agencies are embedded in a political process. A federal agency serves and depends on the support of multiple principals—including public interest groups, the administration, specific regulators, the Congress as a whole, and specific committees within the Congress. The agency will have ambiguous and sometimes conflicting goals as the result of compromises among the principals.

Decisions made by government agencies must take into account fairness and accountability in addition to efficiency.[15] Accountability can mean making decisions in a transparent manner, using standard operating procedures, even if allowing managers greater discretion might lead to more efficient outcomes. It can also mean that decisions to commit the government to actions must be taken by a principal—an elected or appointed official, or a government employee—whose objectives are assumed to be aligned with the public interest, rather than by an agent seeking merely to meet the terms of a contract. Accountability takes on great importance whenever public funds are being expended. Not only must the process for expending funds be followed, but the agency must be able to demonstrate this clearly.

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[14] For a clear introduction, see Wilson (1991).

[15] Efficiency would entail an output produced at the least cost as well as a budget set so that the benefits to society from additional output would just be worth the additional cost.

Fairness is of particular concern in the area of labor relations. Here the government's need to demonstrate fairness by strict adherence to standard operating procedures is further reinforced by the desire of public unions and employee groups to use similar procedures to protect workers. One result is a civil service system with its strengths—an ability to withstand demands for patronage—as well as weaknesses in terms of the limits on managers' discretion to hire, fire, promote, and pay.[16] It is not possible for an agency to satisfy all of the conflicting objectives of its multiple principals. Yet as long as agencies' actions are seen as fair, as long as standard procedures are followed, its actions may still be accepted and criticism deflected.

In addition to broad public goals of fairness, accountability, and efficiency, the literature identifies the following as common objectives for public managers:

- providing the highest quality of output;
- getting the highest budget;
- obtaining the most modern technologies;
- being fair to suppliers, workers, and customers;
- offering continuity of employment to workers; and
- supporting suppliers who may be small or disadvantaged.[17]

In some cases, these reflect the goals of principals—either what they desire or what they perceive to be in the public interest. In other cases, they reflect the goals of the agency's own managers. For example, in addition to pursuing their principals' goals, managers may seek larger budgets or staffs as signals of higher prestige.[18] Controlling their own levels of effort is also a concern. The difficulty is not so much with these objectives (many if not all of which would be shared by private managers) but that public managers may be less constrained by market forces in pursuing them. In the public sector, budget shortfalls due to inefficiency can lead to an increase in appropriated resources. The discretion of public managers to pursue their own objectives is particularly great when they are responsible to many principals with conflicting goals (Dixit, 1997, pp. 378–382).

Principals can use incentives in an effort to align their agents' actions with their goals. Alternatively, they can impose external constraints. For example, in the past, Congress has placed ceilings on DoD civilian employment levels and on the size of headquarters activities. Principals can also set performance goals (such as the percentage of commercial activities that must be contracted out or the number of positions that must be in-sourced) and monitor performance. Because the principals do not have access to much of the information held by the agents, such top down constraints and goals will often appear (and possibly be) arbitrary. The constraints reduce the discretion of the public managers while performance rewards can distort activities; without them, however, managers may not always focus on the goals that the principals feel are most important.[19]

Overall, the literature on the behavior of public bureaucracies rejects the notion that a federal agency in the U.S. could mimic a competitive firm—that it could (or should)

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[16] See Wilson (1991, ch. 16 and 18) for a discussion of how rules and standard operating procedures protect agencies from criticism.
[17] Many of these goals are discussed in Wolf (1988, pp. 70–77).
[18] See William Niskanen's "budget-maximizing" model.
[19] For an understanding of how performance measures can distort incentives, see Heckman, Heinrich, and Smith (1997).

completely isolate itself from concerns about fairness, accountability, and public welfare that make it distinctly governmental.

Given the environment in which government agencies work, it would not be surprising if the DoD's sourcing decisions for goods and services simply reflect political realities. A reliance on in-house production for services may reflect—in addition to the site-specific and perishable nature of many services—the political strength of the civil service and the fact that the business service industry and its labor force have historically been less concentrated and powerful. For example, from an efficiency perspective, there is no reason for 14,000 civil servants to be employed selling groceries to military personnel. Although most evidence is anecdotal, one study of the outsourcing decisions of 3,000 county governments between 1987 and 1992 found quantitative evidence of the effect of politics—counties with highly unionized public employees chose to outsource less (Lopez-de-Silanes, Shliefer, & Vishnay, 1995).

Is It Efficient for Public Producers to Outsource More Than Private Producers?

It is worth asking if government producers—to the extent that they do seek efficiency—would find outsourcing even more attractive than do private producers. In the case of labor-intensive services, limitations in the ability of federal managers to hire, fire, promote, and pay would—even by itself—seem to dictate this. Two factors, however, may at least partially offset these motivations.

One is the need for the government, operating with public funds in the public interest, to keep fraud and conflicts of interest to a minimum. A private firm might, in some situations, outsource some of its financial management or decision-making and treat any loss due to contractor fraud or conflicts of interest as a simple cost of doing business. For a government agency, however, such losses are tied to functions that would be considered inherently governmental—something for which the agency must be directly accountable to the public.

A second reason is that the same factors that make the government less efficient as a producer of goods and services also make it less efficient as a buyer.[20] The literature relating to the need for reform of the civil service system is matched by that citing the need for acquisition reform. The need to demonstrate fairness and transparency, for example, can make it hard for contracts to be awarded to any but the lowest cost bidder, irrespective of more subjective concerns about performance. The balancing of competing objectives that private sector managers appear to use in making sourcing decisions, however effective over the long run, would not readily stand up to scrutiny by the GAO or an Inspector General concerned with transparency and accountability.

Public and Private Production: The Evidence From Outside the DoD

DoD outsourcing decisions would—in theory—be simplified if there was strong evidence that government production under competition was, empirically as well as conceptually, more costly than private production. Some commercial activities would be kept in-house because of acknowledged non-cost benefits of in-house, rather than private production. How many and which ones would remain a source of controversy, but the remaining commercial workloads—current as well as future ones—could be shifted to the private sector without the need for questionable cost analyses or disruptive direct competitions.

Economists may be willing to conclude on conceptual grounds that—in markets with strong competition and no market failure—the public sector has at least no intrinsic

[20] For a discussion that links government problems as a buyer with the nature of public bureaucracies, see Kelman (1990).

advantage over private production. Yet the DoD, faced with the concerns of public employees and the imperfections of real (and often defense-specific), as opposed to idealized, markets, might need somewhat more concrete arguments to make the case for advantages over the private sector for commercial-type activities. What does the empirical evidence, including that from the public–private competitions conducted within the DoD, indicate about the relative costs of public and private production?

In developed economies, public and private producers are not often found side by side in competitive markets, and analytical evidence about the relative performance of public and private enterprises under competition is limited. Nonetheless, there have been hundreds of studies comparing public and private productions, as well as numerous reviews of that literature.[21]

The findings of studies often depend on the type of data used. Comparisons between the performance of public and private enterprises in Europe have focused on industries such as steel or transportation in which economies of scale or public regulation limit competition. Many of these studies have found that public provision is less costly. In contrast, studies that focus on more competitive activities—such as waste collection, street cleaning, or routine building maintenance —that can either be performed or purchased by local governments, generally find that private provision is less costly (Borcherding, Pommerehne, & Schneider, 1982, pp. 127–156). In these studies, however, the cost differential—which is often on the order of 20% to 30%—often reflects not only any intrinsic advantage of private production but also the effects of introducing competition.

Overall, the studies that most strongly assert the efficiency of private over public production are often those that rely on the weakest evidence, and some careful reviewers doubt that there is credible evidence that private production has any intrinsic advantage in relation to public production (Stiglitz, 1991, pp. 15–24).

Overall, this literature leads to the following conclusions:

- Public production might be less efficient than private production.
- If public production is less efficient, the difference may be insignificant.
- Competition seems to drive efficiency more than does the form of ownership.

How is this empirical literature to be reconciled with what is known about bureaucratic behavior and the costs that government agencies incur in managing labor and other resources so as to both demonstrate and provide fairness and accountability?

One answer is that any public enterprise that survives in competition with the private sector on a level playing field is only public in the sense that it is a business owned by the government. If the playing field is truly level, it cannot rely on public funds or the political process for its survival and is thus by definition less of a government agency in the bureaucratic sense. Some authors suggest that, under these peculiar circumstances, its form of ownership has, in practice, changed from "public" to "private" (Boardman & Vining, 1992, pp. 205–239). The fact that the residual value of the enterprise accrues to the government rather than to private individuals may not greatly affect its efficiency.

Another answer is that the playing field may be tilted by hidden subsidies, such as forgone taxes and import duties. Some authors suggest that the apparent success of government enterprises in capital intensive industries is due in part to a hidden capital subsidy (Ayab & Hegstand, 1987, pp. 79–101). The government's borrowing rate—which

[21] See, for example, Tighe et al. (1997).

reflects its ability to raise taxes to cover its borrowing—will typically be lower than that faced by a private firm. Yet capital devoted to a risky commercial activity is not, in any real economic sense, less costly if it is undertaken by the government rather than a private entity.

Each of these issues offers the potential for additional research. However, whether that research addresses the specific issues of the level playing field or the broader question of capital budgeting for asset amortization and depreciation, it will be years before the results are available. In the meantime, public policy needs to use available data to make the best decisions available.

Towards a More Methodologically Sound Sourcing Policy

Regardless of the future of the DoD's in-sourcing initiatives, it seems likely that sourcing policy will be a continuing source of debate and concern to policy makers going forward. In a time of budgetary uncertainty and decline, stakeholders on all sides of the issue will continue to press their cases for how the DoD can best utilize resources to execute the missions it is tasked to perform. CSIS believes that the only way for the DoD and the OMB to make meaningful progress on these issues is to develop methodologies based on the best and most complete data available. As discussed earlier in this paper, this approach will have benefits in any decision the DoD makes that has budgetary implications. Policy makers should always have the most accurate picture available of the true, fully burdened cost implications of the choices before them.

Unfortunately, the literature on how the private sector approaches sourcing decisions does not appear to offer many lessons for the public sector. The way the private sector defines core competencies and focuses on keeping those in-house may provide some useful lessons learned as the OFPP continues to refine its guidance on what functions or positions qualify as inherently governmental or closely associated. But overall, there are too many differences between the way decisions are made and how various costs and benefits are weighted to allow for useful comparisons between how public and private entities approach sourcing decisions.

In the final stages of this research effort, CSIS will be expanding upon its previous work on the subject to support the development of a repeatable, verifiable, data-driven approach calculating the cost of government performance. The CSIS approach focuses on line-item specificity for cost elements, tied to a detailed Statement of Work based on the elements in the following taxonomy (see Figure 1). CSIS has verified that data exist within DoD systems to support at a minimum the ability to calculate a range of cost estimates for each of these elements. Using the data for cost estimating and decision-making will hasten the improvement of both data and cost-estimation methodologies.

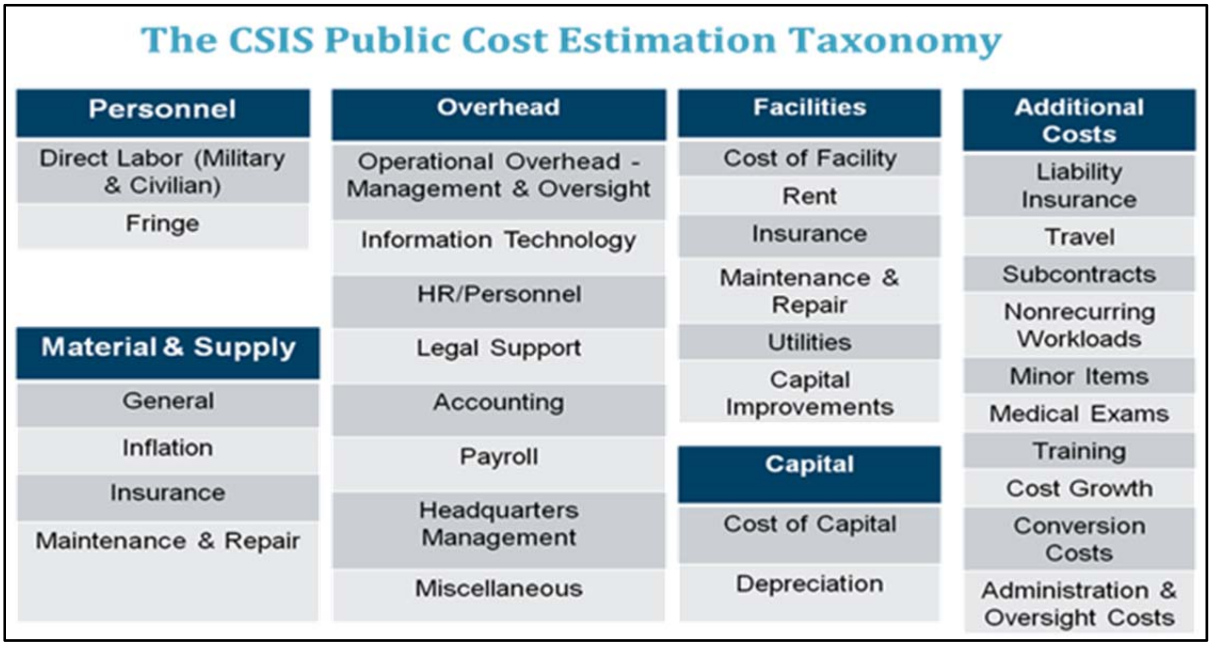

Figure 1. The CSIS Public Cost Estimation Taxonomy
(Berteau et al., 2011, p. 16)

To build upon this taxonomy, CSIS plans to incorporate OMB's Object Class Codes (OCCs) to provide even greater specificity of cost elements. OCCs are used by agencies, including the DoD, for internal financial tracking and by congressional staff for appropriations, and CSIS believes that tying a cost-estimating methodology to this widely used and well-understood cost classification system will provide a basis for a realistic, implementable methodology for capturing the true, fully burdened cost of government performance. By relying on existing data to the maximum extent possible, the DoD can find it easier to calculate better cost estimates and to use those estimates in sourcing and other budget decisions.

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Cost Estimating

Software Should-Cost Analysis With Parametric Estimation Tools

Robert Ferguson
Software Engineering Institute

The Use of Inflation Indexes in the Department of Defense

Stanley A. Horowitz, Alexander O. Gallo, Robert J. Shue, Daniel B. Levine, and Robert W. Thomas
Institute for Defense Analyses

Political Connections of the Boards of Directors and Defense Contractors' Excessive Profits

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An Analytical Synopsis of Dr. Ashton Carter's "Should-Cost" Initiatives

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Quantifying Uncertainty for Early Life Cycle Cost Estimates

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Software Should-Cost Analysis With Parametric Estimation Tools[1]

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Abstract

In Department of Defense (DoD) acquisition contracts there are often concerns of security and competitive advantage making it difficult to find comparable performance data that may be useful in evaluating contractor proposals. In order for programs to make such comparative evaluations, a should-cost analysis may be conducted. This analysis can be compared to a benchmarking process provided that a benchmark database is available. Parametric estimation tools provide this type of data.

This paper shows how SEER-SEM was applied as part of the should-cost effort on the F-22 program. The Office of the Secretary of Defense recognized the resulting $32 million savings in the presentation on *Better Buying Power II*.

Introduction

June 28, 2010, Under Secretary Ashton Carter issued the Better Buying Power memorandum (Carter, 2010) suggesting seven (7) focus topics. “Should-cost analysis” addresses several of the focus areas but most clearly the one Secretary Gates labeled “Incentivize Productivity and Innovation in Industry and Government.” The Department of Defense (DoD) has significant history with should-cost analyses. A RAND study (Boito, 2012), examined this history from the 1970s to today. The RAND study finds support for this analysis in the Federal Acquisition Regulations (FAR) as follows:

> Should-cost analysis as described in the FAR is a specialized form of cost analysis, used to support contract negotiations, that is characterized by a focus on the elimination of contractor inefficiencies. It is significant that the guidance for should cost analysis is found in the federal regulation for the contracting function, because contracting is the process by which the government specifies what it wants to buy and at what price. (Boito, 2012, p. 41)

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In this study, RAND observes that a should-cost analysis requires participation of both contractors and government personnel. Successful negotiation can only be achieved when the contractor agrees to the objectivity of government observations and the contractor believes it can eliminate the inefficiency. The negotiation task is often difficult because the government is frequently in a position of having a single source supplier. The single-source situation may make it difficult for the government to persuade the contractor to participate openly in the should-cost analysis. Any lack of openness or access to data will limit the government's ability to identify the inefficiencies.

A major challenge in conducting a should-cost analysis is the skill required of the analysts. The team doing the analysis must encompass skills in pricing, contracting, program management, and subject matter expertise in areas relevant to the program (Boito, 2012, p. x). This team must have both depth of knowledge in the focus disciplines and breadth of experience across programs and industry. Finally, they must be able to apply these skills to present an objective set of recommendations accessible to both program management and contractor.

The Software Engineering Institute (SEI) has participated in some should-cost analyses using parametric software cost estimation tools. This paper describes the methodology and some results. The following section describes the methodology. Then next section discusses an example application and results synthesized from multiple cases. The final section provides lessons learned and ideas for future improvements.

SEI Should-Cost Methodology

The DoD may have gotten an early start on everyone with "should-cost analysis," but the commercial world has pursued the topic extensively under the label of "benchmarking." An early book on the subject is *Benchmarking: The Search for Industry Best Practices That Lead to Superior Performance* by R.C. Camp (Camp, 1989). Just a year later, James Womack, Daniel T. Jones, and Daniel Roos (1990) described Toyota's use of benchmarking in *The Machine That Changed the World*. In the 1990s, corporate benchmarking was a popular consulting business.

The SEI should-cost work stemmed directly from SEI experience with benchmark databases in the form of parametric cost estimation tools. Using the parametric estimation tools is not quite the same approach as traditional benchmarking, but the cost of this approach is modest and works well considering the resistance to traditional benchmarking in the DoD acquisition context.

Five steps are required to prepare a should-cost proposal using parametric estimation tools.

Step 1: Develop a detailed understanding of the proposer's estimate. Include product scope, architecture, and methods of development by reviewing the proposal and proposer's basis of estimate.

Step 2: Use a parametric estimation tool to develop an estimate that matches the proposer's estimate as closely as possible. Estimates of size must match exactly.

Step 3: Perform a sensitivity analysis to identify the productivity factors having the greatest effects on program performance.

Step 4: Prepare an alternative estimate with the adjusted parameters. Develop a briefing demonstrating the changed parameters and new estimate.

Step 5: Conduct a workshop to help the contractor plan potential performance improvements.

Step 1: Develop a Detailed Understanding of the Proposer's Estimate

This step will require access to many details of the contractor's basis of estimate and some interviews with the contractor's staff. This step requires access to the program management and engineering staff who provided the size, product complexity, and project environment factors used for the estimate. Usually, the interviews will require a full day and may require an additional phone call to understand the contractor's meaning and intent for some data. Analyzing the basis of estimate may require as much as five to seven days in total. Understanding the scope of work and complexity of the proposed product is not easy since the WBS (e.g., task sheets) structure of the proposal may cause parts of the estimate to be represented in several different sections.

- Begin preparation by reviewing product requirements, including proposed product architecture. Identification of complexity factors such as aggressive key performance measures, safety, interfaces, and others will be essential to preparing the estimate.
- Provide the contractor with requirements for data and interviews.

With the contractor, complete the following:

- Review analogies used for developing the size estimate. Did setting the size follow a standard procedure used previously by the company? Is there any reason the size would have been adjusted to meet a target price? Use these factors to set a potential range for the size estimate.
- Check the scope definition to see which components and work products will be delivered and to whom they will be delivered. Count every delivery outside the development team (e.g., product certification and public demonstration).
- Check the domain definition and whether the product is considered to be new or a modification and enhancement.
- Identify the collection of task sheets representing the WBS that will be utilized by the estimation tool. Sum up the efforts on these task sheets that correspond to the estimation tool outputs.
- Review the definition and computation of application complexity. Specifically look for performance criteria and quality attributes that may represent specific baseline attributes in the estimation tool knowledge base. This step is important because there may be inconsistencies between the proposer's use of terminology and the tool's knowledge base use of the same terms. For instance, some performance requirements might use the phrase "real time" to mean "very fast" where the normal interpretation is "deadline driven."
- Review "Manager's Checklist for Validating Software Cost and Schedule Estimates" (Park, 1994) to confirm satisfaction with the contractor's estimation process and resulting basis of estimate.
- Document the size estimate and the knowledge base factors to be applied for each component that will be estimated. The size values should be the current baseline product, proposed reuse, modification, and new development. Use of proxy measures such as ESLOC will add uncertainty to the estimate.

At the completion of this step, you should be ready to supply the parametric inputs in the next step.

Step 2: Match Proposer's Estimate

The purpose of this step is to use the parametric tool to produce an estimate that matches the contractor's estimate as closely as possible. The estimates should match, within a small difference on size, effort, schedule, and defects. Many different parameters must be tested to achieve a satisfactory result.

Perform the following activities during this step:

- Clearly identify as much of product context as the tool allows. Most tools allow specification of product domain (e.g., avionics), development methodology, and development language.
- Begin by entering base, new, modified, and deleted size estimates. ESLOC can be used as a last resort, but this increases the uncertainty in the estimate. It is not possible to use an ESLOC value to back out the base, new, modified, and deleted values.
- Record additional estimation tool parameter values such as
    - available tools and platforms,
    - experience of team members in both development and architecture,
    - organizational process maturity,
    - quality assurance and testing, and
    - factors affecting team performance, such as cohesion and geographical proximity.

  Detailed familiarity with the parametric tool is required for this step. DoD contractors are and will claim to be high-caliber development organizations. Interviews are a good mechanism for obtaining the parameter values, but experience and judgment are necessary for trustworthy results.
- Modify the parameter values of the baseline to match the contractor estimate. This step may be difficult and tedious. Even a fairly simple tool like COCOMO II has 22 factors affecting productivity plus various sizing factors. Once the initial estimate is prepared with contractor sizing and product domain information, it is time to match the contractor estimate by adjusting quality and productivity parameters.
- Save the matched estimate as a baseline.

If no reasonable match can be made, then it is time to re-check the Park (1994) checklist and re-interview the contractor. Most likely, there is a misinterpretation of some size measure, knowledge base parameter, or performance parameter. It is also possible that the contractor's WBS has been misinterpreted.

Step 3: Perform Sensitivity Analysis

The sensitivity analysis is necessary in order to make concrete suggestions about productivity improvements. Productivity parameters will include such factors as team cohesion, developer experience, project environment, and process maturity. Product quality parameters will address questions about the target environment, testing, and stability of the

specification. Parameters affecting product quality should generally be excluded from the sensitivity analysis unless some error has been identified in the proposal.

- If the tool provides a sensitivity analysis, then use the suggested top 10 parameters for improvement potential. If the tool lacks this capability, it may be necessary to apply brute force or Monte Carlo methods to determine the parameter sensitivity.
- List the parameters to be tested for alternative estimates.

Step 4: Prepare Alternative Estimates

- Re-run estimates with the identified performance criteria set to revised values. The revised values are selected from benchmark data. These values may be taken from the best projects in the tool vendor's database or another source.
- Document the alternative schedule, effort, and defects along with the revised resource allocation (how much effort is suggested for top few roles).
- Save the new baselines with identification.
- Document the changes to the affected parameters.
- Document the differences from the contractor's baseline in schedule, effort, defects, and cost.
- Run a second sensitivity analysis. If the sensitivity analysis suggests significant additional improvements are possible, then repeat this step and develop a second should-cost estimate and proposal.

Summarize the results in a briefing making comparisons of estimated results and alternative parameter values. Associated with each alternative should be a discussion of the rationale for the potential improvements and how they might be achieved. If more than one estimate will be presented, then be prepared to discuss the relative improvement achieved by each.

Step 5: Workshop

The workshop begins with a presentation of the analytical results and concludes with some recommendations for action. A workshop is necessary as the contractor must agree to planning and resourcing to make changes.

- Display the baseline estimate beginning with the usual values: size, effort, schedule, and defects.
- Show the sensitivity analysis used to arrive at the new estimation parameter values.
- Provide the actual list of parameter values applied for the new estimate.
- Display the revised estimate showing the comparison of the values to the baseline.
- Provide comparisons and explanations of initial and revised parameter values.
- Allow contractor evaluation of potential for change.
- Achieve agreement on action items to resource changes.

Results

The SEI participated with AT Kearney (ATK) in a should-cost analysis for the F-22 3.2a contract. The SEI used the method described here and ATK applied bottom-up analysis. Both approaches led to very similar cost savings, which gave the resulting recommendations very strong weight. As a result of this should-cost effort, the program office was able to negotiate a 15% reduction, $32 million cost savings. These results were reported in a recent OSD (2012) publication *Better Buying Power II.*

There were several lessons learned during this effort. Many of the lessons correspond to the recommendations in the aforementioned RAND report.

1. A dedicated independent team is needed. This team was focused on the should-cost effort and not distracted by contracting and immediate technical problems.
2. Use of multiple methods for should-cost has value to program. The methods used by ATK and SEI were independent and different. The results were similar and carried a great deal of weight in negotiations because of the independence.
3. A contractor's estimation procedure based solely on historical data is insufficient. Such contractors' estimates may be defensible but miss the opportunity for benchmarking against competition and industry-wide comparisons. Should-cost is a method that requires available benchmarks for both cost and quality and specifically identifies the driving factors behind cost and quality.
4. The contractors' usage of estimation tools must be examined carefully. Contractors may change the cost estimation tool's baseline data in order to match contractor performance history. This approach can compromise the ability to use the parametric model as a baseline. Using the parametric model as a benchmark required significant analysis to arrive at a baseline value that matched the contractor's. Contractors had misinterpreted some input productivity factors and adjusted the output calculations instead.
5. Not all parameters are easy to identify. For example, SEER makes use of a parameter that can be used to account for independent development teams when size has not been partitioned to the component level in the estimate. Partitioning the work allows for a more aggressive schedule estimate since teams are able to operate independently until integration testing. This may be difficult to detect from the available documentation.
6. Consider the effects of adding automation or tooling to testing and other process changes. Cost savings are often made possible by making process changes; however, process changes can take time to execute. Some savings that were suggested in the F-22 analysis were not achievable within the time horizon of the 3.2a effort. Recommendations will be accepted or rejected as part of the negotiation process.

There were a number of reasons to consider the F-22 analysis a success. The government certainly was happy to negotiate a better price. Even though some of the work between analysts and contractors was contentious, the contractors were able to agree to a number of suggested improvements. An additional should-cost analysis was also conducted for the next contract block. The second time through there was already evidence of improved performance and much less contention during the analysis.

It will be a while before the final numbers are available from the F-22 modernization work. Hopefully, that will also be a success story.

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The Use of Inflation Indexes in the Department of Defense

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Abstract

The 2009 Weapon System Acquisition Reform Act (WSARA) requires the DoD's Office of Cost Assessment and Program Evaluation (CAPE) to "periodically assess and update the cost (or inflation) indexes used by the Department to ensure that such indexes have a sound basis and meet the Department's needs for realistic cost estimation." The objective of this paper is to provide CAPE with a factual and analytical basis for responding to this provision of WSARA.

The paper starts with a discussion of the rationale for using inflation indexes in general, in the government as a whole, and in the DoD. It then identifies the regulatory and statutory provisions that support the issuance of inflation guidance by the Under Secretary of Defense

(Comptroller; USD[C]). Next, it describes how this guidance is applied by describing the key features of the processes used in the Office of the Secretary of Defense (OSD) and the Services to adjust for inflation in estimating the costs of and budgeting for major systems. It evaluates the appropriateness of using the inflation indices provided by the USD(C). Finally, it compares the Comptroller's rates with some alternatives and considers whether modifications to current practices might better meet the DoD's needs for realistic cost estimation.

Introduction

The 2009 Weapon Systems Acquisition Reform Act (WSARA) requires the DoD, Office of Cost Assessment and Program Evaluation (CAPE) to "periodically assess and update the cost (or inflation) indexes used by the Department to ensure that such indexes have a sound basis and meet the Department's needs for realistic cost estimation." The objective of this paper is to provide CAPE with a factual and analytical basis for responding to this provision of WSARA. Because WSARA is concerned with the cost of major systems, much of our attention is given to the treatment of inflation by Major Defense Acquisition Programs (MDAPs).

In the next section, we present a discussion of the general rationale for inflation and price indexes, whether applied to the economy as a whole, to the government, or to the DoD. In the section The Derivation of Inflation Indexes for Use by the DoD, we describe how DoD price indexes are developed. We address (a) the regulatory and statutory provisions that govern the issuance of inflation guidance by the Under Secretary of Defense, Comptroller (USD[C]), and (b) how these provisions are applied by describing the key features of the processes used in the Office of the Secretary of Defense (OSD) and in the Services to produce inflation guidance.

In the next two sections, we turn to how the DoD uses the deflators and other considerations in budgeting and in cost analyses related to procurement. We then discuss the current practices by the DoD in general and by the Services. In the section Analysis of Alternative Deflators for MDAPs, we compare the USD(C)'s price index for procurement with alternatives, principally the national defense indexes published by the Bureau of Economic Analysis (BEA), and defense-related relevant producer price indexes published by the Bureau of Labor Statistics (BLS). The purpose of these comparisons is to explore the possibility that modifications to current practices might better meet the DoD's needs for realistic cost estimation.

We next assess current DoD practices for accounting for inflation; and in the final section, we present concluding observations and recommendations.

We are careful, in discussing price indexes, to differentiate between those that cover the entire economy and those that cover specific classes of goods and services. The former we generally refer to as inflation indexes and the latter as price indexes or escalation indexes.

The General Rationale for Inflation Indexes

The purpose of inflation and other price indexes is to relate changes in the quantity of resources bought or sold to the amount of money spent on them (Allen, 1935, p. 58). Price indexes identify and isolate the effect of price changes. Removing the effect of price changes leaves information on quantity, or real, changes. Indexes permit us to answer questions like the following[1]:

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[1] Conceptually, a price index measures the ratio of expenditures under two alternative price systems that provide quantities of goods and services of the same value.

- What has been the change in the real size of the economy over time?
- What effect have changes in the DoD budget had on the resources taken from the economy and the resources available to the DoD?
- How much real cost growth has there been in particular DoD procurement programs?

Price indexes are meant to capture changes in the price of a particular level of capability. They should not capture price changes that are due to changes in the quality of products. As an example, the availability of much better computers at only slightly higher prices means society has gotten richer in real terms. Allowing price indexes to rise with price increases associated with quality improvements would make this appear not to be the case, so price indexes should *not* reflect the price of quality improvements. In other words, the portion of price changes that reflect quality improvements should be subtracted from price indexes. (We will later see that BEA and BLS indexes follow this procedure.)

Price indexes can be developed for different classes of goods and services: the economy as a whole; all DoD spending; DoD procurement; specific types of DoD goods such as aircraft, ships, and computers; and the input prices facing firms that produce things for the DoD. Price indexes for different kinds of goods and services can vary substantially over time. Figure 1 shows how indexes for commercial goods and services have varied with the type of good and over time during the last 40 years. Some types of goods and services have moved along with the overall consumer price index (CPI). For example, the price of apparel has risen far more slowly, and the price of medical care has climbed at nearly double the overall rate since 1970.

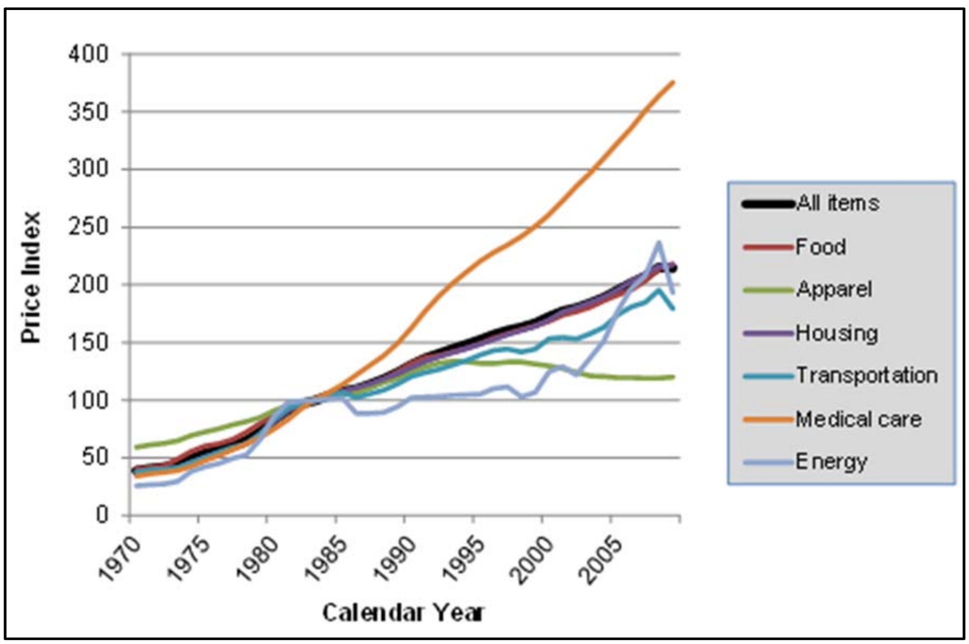

Figure 1. Consumer Prices for Selected Classes of Major Expenditures
(Administration of Barack Obama, n.d., Table B-60)

The fact that one index has not fit all cases of commercial goods suggests that budgeting defense goods for the future should also distinguish between types of goods. In an International Monetary Fund paper, Premchand (1983) put it succinctly: “Every budget is formulated, either explicitly or implicitly, on a price basis. As prices rise and become

relatively unpredictable, the problems of budgeting are felt more keenly" (p. 242). Using different price indexes for different goods can help to ameliorate these problems. The BEA, which produces the U.S. National Income and Product Accounts, notes that the use of a price index is appropriate if its definition and coverage closely match the category of product to which it is applied (BEA, 2009).

Different organizations take different approaches in accounting for inflation in budgeting. Organizations such as the Treasury and the Office of Management and Budget (OMB) that are involved in financing aggregate government expenditure focus on broad issues, such as the balance between the public and private sectors, and particularly on the value to the private sector of resources taken for public purposes. These offices commonly analyze these issues using the GDP deflator, an index based on the price of the market basket of all goods and services provided to final users by the entire U.S. economy.[2] By comparison, organizations such as the DoD Comptroller's office that are responsible for the budgets of particular government agencies frequently use indexes that reflect the prices of the specific resources their agencies buy to support their activities (Premchand, 1983, pp. 246–247). A possible compromise would use specific indexes to develop budgetary requirements and a broad index to reflect the constant-dollar burden implied for the economy as a whole.

The Derivation of Inflation Indexes for Use by the DoD

This section has three objectives:

- to identify the regulatory and statutory provisions that authorize and prescribe the issuance and use of guidance related to inflation in the DoD;
- to describe the flow of information for developing the economic assumptions, including those for inflation, used in generating the President's Budget; and
- to describe the five price indexes constructed by OMB and how they are used to develop the Comptroller's appropriation-specific deflators.

Regulatory and Statutory Basis

The statutory requirement for all government budgeting is contained in Title 31 of the *United States Code* (U.S.C.), § 1104, entitled "Money and Finance." This title directs the President to create an annual budget, delegating administrative authority to the OMB.[3] The OMB requires every agency to prepare an annual budget for its spending that expresses the administration's most recent policy objectives (31 U.S.C. § 1109).[4] OMB forms these inputs into a total annual "policy" budget called the President's Budget.

The President's Budget consists of spending for two types of programs:

- discretionary programs, such as DoD procurement line items, which are funded at a level decided by Congress every year; and

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[2] GDP is the sum of consumption, investment, government spending, and exports minus imports.
[3] 31 U.S.C. § 1104 resulted from the Budget and Accounting Act of 1921. Administrative responsibility initially existed within the Bureau of the Budget, with the OMB tasked through Executive Order in 1970.
[4] The OMB also prepares a "baseline," or "current services" budget, that assumes that current-year programs will extend into the budget year and out-years, and updates their costs using the most recent economic assumptions.

- mandatory programs, such as Social Security and Medicare, which are passed as permanent law by congressional authorization, written into the U.S.C, and funded by annual appropriation as directed by the permanent law.

This paper concerns inflation for only the discretionary programs. The following paragraphs describe the general guidance contained in OMB Circulars A-11 and A-94 and the specific guidance to DoD Components in the Financial Management Regulation (FMR), issued by the OUSD(C), for meeting the OMB guidance.

OMB Circular No. A-11 (2009) sets policy for how agencies are to treat inflation in their budget requests submitted for executive review. The relevant excerpt from Section 31 (Paragraph 31.1(c)) of the circular provided below states that agencies must ensure that their inputs to the discretionary part of their budgets must be consistent with the OMB's economic assumptions, including those relating to inflation.

> (c) ***What economic assumptions should I use when I develop estimates?***
>
> All budget materials, including those for the outyear policy and baseline estimates, must be consistent with the economic assumptions provided by OMB. The specific guidance below applies to outyear policy estimates.
>
> OMB policy permits ***consideration*** of price changes for goods and services as a factor in developing estimates. However, this does not mean that you should automatically include an allowance for the full rate of anticipated inflation in your request. …
>
> For ***discretionary programs***, you may include an allowance for the full rate of anticipated inflation, an allowance for less than the full rate, or even no allowance for inflation. In many cases, you must make trade-offs between budgeting increases for inflation versus other increases for programmatic purposes.[5]

OMB Circular No. A-94 (1992) provides agencies with guidance for cost-benefit analyses. It recommends using the gross domestic product (GDP) deflator for the overall inflation rate—the general increase in prices of goods and services—but permits using sector-specific indexes that differ from the general inflation rate "where there is a reasonable basis for estimating such changes." Projects with a budget horizon longer than six years (the Future Years Defense Program (FYDP) years in the case of the DoD) are advised to use the final year's rate in perpetuity.

The Financial Management Regulation (FMR) 7000 14-R (DoD, n.d.) provides inconsistent guidance concerning price indexes in two paragraphs of Volume 2A, Chapter 1, Section 010303. Paragraph B.1 states that DoD budget estimates should "reflect the most likely or expected full costs." Paragraph B.2, however, mandates that "price level changes will be based on data provided by OUSD (Comptroller)," and that the Comptroller's appropriation-specific price indexes should be used to "determine the amount of price escalation for a procurement line item, major RDT&E system, or construction item over a given time period." This guidance is being revised to make it clear that the most likely or expected full costs in then-year dollars should be used in budget preparation—even if this implies price increases different from those implied by Comptroller's indexes—and that Comptroller indexes must be used to convert then-year dollar values to constant-dollar values.

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[5] This section is titled "Compliance With Administration Policies and Other General Requirements" and is the only inflation guidance that appears in the 1,000-page document.

Paragraph B.2 seems to direct the use of the Comptroller's indexes as the only acceptable value for calculating price escalation for specific programs, while the "most likely or expected full costs" of paragraph B.1 are presumably those for the specific items being purchased (DoD, n.d.). This appears inconsistent because the Comptroller's indexes are not at all specific to the particular goods being purchased.

Development of Economic Assumptions

Each fall, senior officials and staff from the OMB, the Council of Economic Advisors, and the Department of the Treasury (collectively known as the "Troika") draw on administration policies and use various forecasting models to produce a 10-year forecast of key economic indicators, including inflation. These economic assumptions update previous assumptions to reflect recent data. They are used in forming budget outlay and revenue estimates and developing the annual President's Budget.

The OMB provides the economic assumptions regarding inflation[6] to the federal agencies each November as guidance. That guidance, and how the DoD Comptroller uses it to develop more detailed guidance for DoD Components, is discussed next.

Derivation of Appropriation-Specific Price Indexes

OMB guidance sent to the OUSD(C) covers the two prior years, the budget year, and four out-years for five categories of funding:

- Military pay, using the projected Employment Cost Index (ECI) for wages and salaries published by the BLS, of the Department of Labor, adjusted for administration policy recommendations as prescribed in Title 37 U.S.C. Section 1009
- Civilian pay, using the projected ECI less 0.5 percentage points, adjusted for administration policy recommendations, as prescribed in Title 5 U.S.C. Section 5303
- Fuel, using the projected Energy Information Administration Refiner Acquisition Cost; this is the oil refiners' average price for crude oil
- Medical, using the projected BLS Consumer Price Index for All Urban Consumers (CPI-U) Medical price index
- Other purchases—all purchases other than the four categories just listed—using the projected values of BEA's GDP price index as determined by the Troika and provided to the Comptroller by the OMB

The OUSD(C) uses weighted averages of these five OMB indexes to construct the annual price indexes (often called deflators) for the DoD appropriation-level accounts shown in Table 1. The weights are based on how the spending for each account is distributed across the resources represented by the OMB indexes (military pay, civilian pay, etc.).

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[6] The Administration's economic assumptions include projections of consumer inflation measured by the urban Consumer Price Index, GDP (Current, Real, and the Price Index between them), Unemployment rate, 91-day Treasury Bill interest rate, and 10-year Treasury Bill interest rate. They are available in the OMB's "Supplemental Materials" (see OMB, n.d.).

Table 1. Composition of Appropriation Level Inflation Deflators
(Office of the Under Secretary of Defense, Comptroller [OUSD(C)], 2010)

Appropriation (FY 2010 Outlays)	MilPay	CivPay	Fuel	Medical	Other Purchases
Military Personnel ($155.0B)	61%			8%	31%
O&M ($279.7B)		30%	5%	12%	53%
Procurement ($147.2B)					100%
RDT&E ($79.3B)		11%	<1%		89%
Military Construction ($23.8B)		5%			95%
Family Housing ($3.3B)		4%	1%		95%

The OMB directs that, in deflating program spending for years beyond those for which indexes have been made available, program managers should extend the final year's inflation rate into the later years (OMB, 1992, Section 7.b.).

The table illustrates the process for the FY 2010 budget. For example, 30% of total DoD spending on operations and maintenance (O&M) was for civilian pay. The O&M index was therefore calculated as follows:

O&M index = (CivPay index) x 0.30 + (Fuel index) x 0.05
+ (Medical index) x 0.12 + (Other Purchases index) x 0.53

It is significant that while the first four OMB indexes characterize specific types of resources (civilian pay, etc.), the last one, "other purchases," does not. In fact, the OMB index for all other purchases is the GDP deflator, the single price index for all spending on U.S. goods and services. The GDP deflator is the main determinant of the amount of inflation allowed in the DoD budget. It is the sole determinant for procurement spending and is applied to fully 64% of total spending. (Weighting the "other purchases" percentages in the last column of Table 1 by the proportion of total outlays implied in the first column yields a weighted average of 64%.)

The OUSD(C) deflators are issued to the DoD Components by guidance memo. The assistant secretary (financial management and comptroller) of each military department issues implementing guidance to its commands and components that is tailored to its department's administrative procedures. The components use the deflators and instructions contained in the DoD FMR to re-price the President's Budget through a resource management decision for submission to the OMB, and also to prepare detailed budget justification material for submission to the Congress.

Current Practice for Incorporating Inflation Into Program Budgets and Cost Estimates for Major Defense Acquisition Programs

The DoD buys millions of different products: food for Service mess halls, spare parts, construction material, medical supplies, medical equipment, construction equipment, and many others. In these instances, the DoD buys at prices generally available in the market to large buyers. Price indexes for these kinds of commodities are properly based on their output prices. Such indexes might often approximate a broad-based index like the GDP deflator.

In this paper, we do not focus on these kinds of purchases. We are interested specifically in MDAPs because they are the focus of WSARA. Contracting procedures require that the prices of major defense systems be based on the costs of the inputs to the systems: labor and materials. This is even true of fixed-price types of contracts. Firm-fixed-price contracts are based on the expected cost of inputs, while fixed-price with economic price adjustment contracts incorporate fluctuations in labor or material costs during the period of contract performance. It appears that the use of price indexes based on the relevant input prices is best for MDAPs.

In this section, we provide an overview of the treatment of inflation by MDAPs and then turn to the practices of the individual Services.

General Considerations in Use of Inflation Indexes by Program Managers

Program budgeters have to think about inflation for two reasons:

- In budgeting, they must estimate the future costs of their procurement programs in then-year dollars that are based on expected increases in prices.
- They must calculate real cost increases of systems being acquired in constant (inflation-corrected) dollars, also termed real cost growth. Such calculations are used to identify systems that are suffering from high levels of real cost growth, a focus of WSARA.

In addition, all parts of the DoD must use price indexes to translate budget submissions developed in then-year dollars to constant-dollar terms.

Regarding budgeting, for a program to be fully funded, money must be appropriated up front to cover all projected future then-year costs of the portion of the program authorized in a given year, such as a specified annual production lot. If planners underestimate the extent to which the cost of the authorized program will rise over time, due to either unanticipated general inflation or increases in the prices of inputs specific to the program, appropriations will fall short and an overrun will occur—an undesirable outcome. We noted earlier that guidance regarding the treatment of inflation in budgeting appears inconsistent, calling for the use of OUSD(C) deflators and also mandating use of "most likely or expected full costs." As we shall see, some DoD organizations rely on the Comptroller's projections of inflation for developing then-year budget estimates, while others do not.

Real cost growth is measured by the percentage increase in unit cost relative to a past baseline evaluated in baseline-year constant dollars. The baseline cost can be either the original program cost or a later estimate, depending on the program's history. For procurement programs, the Nunn-McCurdy Amendment to the 1982 National Defense Authorization Act requires the DoD to identify for special attention those programs whose average unit cost growth has breached stated thresholds.

Selected Acquisition Reports (SARs) are used as the source of information concerning cost. The GDP deflator is always used to convert current-dollar costs to constant base-year dollars both for establishing the real cost baseline and for calculating real cost growth.

We now turn to the specifics of how various DoD organizations incorporate inflation into their program budget estimates.

Practices of Individual Organizations

In this section, we briefly describe the procedures various DoD organizations use in incorporating inflation into program procurement budgets. Information in this section is

based on discussions with staff in the organizations cited. Because not all relevant organizations have been contacted, this is not a complete survey.

Army

The Army follows OSD budget guidance without exception in adjusting program costs and budgets for inflation.[7] The indexes the Army uses are stored together with the standard Navy and Marine Corps indexes on the Navy Center for Cost Analysis's (NCCA's; n.d.) website tool for calculating inflation factors.

Navy and Marine Corps

NAVSEA Projections of Shipbuilding Cost. The Naval Sea Systems Command (NAVSEA) follows a systematic methodology to develop its own estimates of inflation for budgeting its ship programs. NAVSEA developed this methodology in response to a 2004 direction from the Under Secretary of the Navy for Acquisition.

NAVSEA has developed a complex and detailed model for making these estimates based on current and historical data on labor and material inputs. Labor prices reflect shipyard-specific labor and overhead rates based on shipbuilder forward pricing rate agreements (FPRAs).[8] Material prices include class-specific material inflation and vendor base adjustments unique to each ship type's market sector (nuclear, non-nuclear, commercial, etc.). Estimates of future prices are based on forecasts by Global Insight, a private firm that has been involved in economic and financial analysis and forecasting for many years. Historical indexes for labor cost increases are based on actual shipyard data, aggregated to the national level based on the workload at each shipyard. Historical material indexes are based on BLS producer price indexes.

NAVSEA's projections of shipbuilding cost increases are higher than the procurement cost forecasts issued by OUSD(C). NAVSEA estimated annual shipbuilding inflation at 3.3% during 2010–2015, while the OUSD(C) procurement index (the GDP deflator) increased at an average annual rate of only 1.5%.

NAVAIR Pricing Models. The Naval Air Systems Command (NAVAIR) develops its own projections for pricing naval aircraft (fixed- and rotary-wing). In a similar fashion to the NAVSEA model, NAVAIR develops estimates for labor and material cost increases and uses these to develop estimates for airframe, engine, and electronics, which are then combined into an overall estimate for fixed-wing aircraft flyway cost.

The variance in these year-to-year projections is surprising. Note, for example, that aircraft inflation is forecast to be halved from 2015 to 2016.

NAVAIR also makes detailed projections for helicopters and missiles. Future labor rates are based on projections for the labor contracts of the major aircraft and missile manufacturers, and materials prices are derived from estimates by Global Insight.

Marine Corps. Marine Corps policy is to use the prescribed OUSD(C) inflation factors for program budget and cost estimates. No exceptions have been identified.

Air Force

Air Force policy for inflation adjustments is decentralized, unlike that of the Army and Navy. Program offices may develop their own inflation projections using industry-specific

[7] Discussion with personnel in the Army Cost Analysis Agency.

[8] An FPRA is a written agreement negotiated between a contractor and the government to use certain rates during a specified period for pricing future contracts or modifications.

prices. These estimates, however, are subject to review by program executive officers, Service acquisition executives, the Air Force Cost Analysis Agency (AFCAA), and the pertinent OSD offices. The description below is based on personal communication from the staff of AFCAA and other organizations.

Air Force Aircraft. Most Air Force aircraft program offices estimate future program costs using specific inflation rates obtained by combining labor and material price rates, commercial forecasting model estimates, and contract information on FPRAs. The methods they use appear similar to those adopted by NAVAIR.

Space Systems. Most programs use specific rates developed from historical data on inflation in space systems and comparisons with general inflation.

Information Technology. Most programs appear to use OUSD(C)-promulgated rates.

National Reconnaissance Office

The National Reconnaissance Office (NRO) purchases optical- and radar-imaging satellites for reconnaissance and surveillance missions. The NRO in 2004 compared its contractors' labor and material prices with the standard inflation guidance for 1995–2001. Labor prices increased by 4.2% per year on average, but material prices showed no upward trend. Combining the labor and material prices with the appropriate weights yielded an average annual inflation rate of 3%. The OUSD(C) procurement deflator increased by 1.4% annually during the same period (Odom, 2004). The NRO bases its budget and cost estimates in large part on Global Insight direct labor and material price indexes.[9]

Summary

We have seen that some DoD organizations develop specialized inflation indexes for their programs and use them to ensure that their budget submissions "reflect most likely or expected full costs." These indexes are used both for development of cost estimates for programs in then-year dollars and for budgeting. These rates can be substantially higher than those provided by the OMB.

Real program cost and cost growth for MDAPs are then calculated using the GDP deflator to convert current dollars to constant dollars.

We now turn to a comparison of the OUSD(C) price index—the GDP deflator—with other alternatives developed by BEA and BLS. Our interest here is in seeing whether using price indexes tailored to different defense goods such as aircraft and ships might offer DoD better tools for accounting for inflation.

Analysis of Alternative Deflators for MDAPs

Introduction

Note by way of background that all DoD procurement outlays, including MDAPs, account for less than 1% of the GDP. There is no particular reason to believe that DoD procurement prices move in tandem with the other 99% of the economy. Moreover, using a

[9] We have not comprehensively surveyed the defense agencies or other organizations to establish their policies with respect to projecting inflation. Most such organizations do not have substantial procurement budgets. Those that do have substantial procurement budgets include the Special Operations Command, the Defense Communications Agency, and the National Security Agency, but we do not have information for them.

single price index for all MDAPs ignores the differences among the various military goods that are procured and the markets from which they are bought.

We proceed by first comparing the distribution of DoD purchases with those in the economy as a whole and then comparing DoD inflation for various procurement categories with other inflation indexes of possible interest and with the GDP deflator. After that, we consider the issue of accurately forecasting inflation.

The Distribution of Spending Across Economic Sectors

Figures from Inforum show that the top 10 sectors that the DoD buys from are, with the exception of wholesale trade, all different from the top 10 sectors for the economy as a whole.[10] The 10 sectors account for roughly half of all purchases in both categories, excluding direct purchases of labor.

Because the DoD and the overall economy purchase very different mixes of items, using the GDP deflator to represent price changes for defense purchases is questionable. Alternative price indexes might provide a better representation.

Retrospective Comparison of GDP With Alternative Price Indexes

Bureau for Economic Analysis National Defense Deflators

In addition to the GDP price deflator, the BEA publishes deflators for procurement of five major types of military systems: aircraft, missiles, ships, vehicles, and electronics. Figure 2 and Table 2 compare these defense deflators to the GDP deflator during the 1985–2009 time period.[11]

The defense deflators are "quality adjusted" to measure price changes, holding the physical specifications of the systems, or their "quality," constant. Examples of quality adjustment for aircraft are features, such as engine improvements. The BEA measures the value of quality changes by their cost of production and excludes them from the price index by subtracting the average quality production cost from the average total production cost (Ziemer & Kelly, 1993; Foss, Manser, & Young, 1993). The BEA deflator is thus influenced by changes in average cost due to factors other than improved specifications, such as changes in input prices. According to the BEA, it may be difficult to estimate the quality change when an entirely new kind of aircraft, such as UAVs, is introduced, leading them to consider the entire price as quality change.

[10] The figures are from 360 sector databases developed by Inforum (The Interindustry Forecasting Project at the University of Maryland). The DoD figures are from the "Federal Defense" table and the economy-wide figures are from the "National" table. ("National" combines spending for federal defense, federal non-defense, non-federal government, and the private sector; Inforum, n.d.).

[11] These BEA deflators are expenditure-weighted averages of separate deflators for durables (largely spares, modifications, overhauls, and support equipment) and gross investment (new equipment). The data are from BEA National Income and Product Accounts Table 3.11.4, Price Indexes for National Defense Consumption and Gross Investment (BEA, 2013).

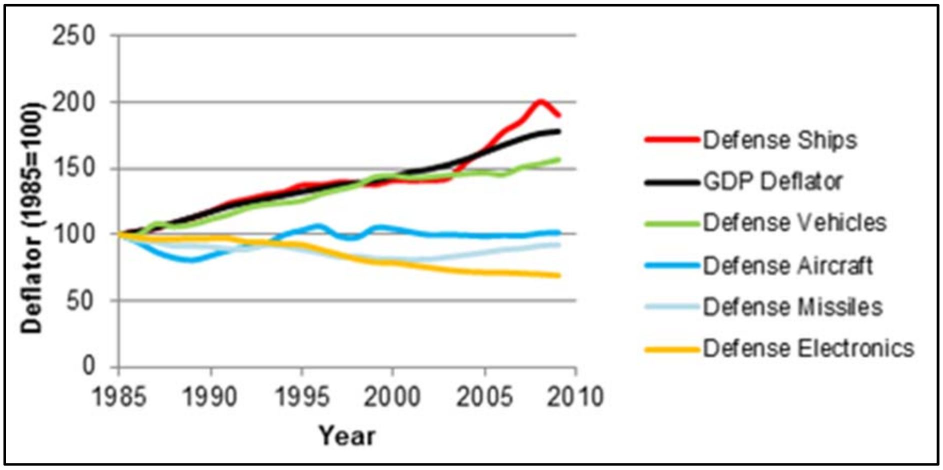

Figure 2. GDP vs. BEA National Defense Deflators

Table 2. Comparison of BEA National Defense Deflators

Deflator	Average Annual Growth Rate 1985–2009	Total Growth 1985–2009
Defense Ships	2.7%	90%
GDP	2.4%	78%
Defense Vehicles	1.9%	56%
Defense Aircraft	0.1%	1%
Defense Missiles	-0.3%	-8%
Defense Electronics	-1.5%	-31%

The BEA deflators in Figure 2 show wide variation: (a) substantial deflation over the period for electronics (which includes software), (b) virtually no change in the indexes for aircraft and missiles, and (c) substantial inflation for ships and vehicles. The large decline for electronics is due to the fact that computer speed, memory, and storage capacity have been rising faster than price for many years. The table and figure show that all of the BEA national defense deflators except for ships have had measurably to substantially less growth than the GDP deflator over the period. The wide variations, however, may be due to how the BEA identifies and measures quality adjustments.

Bureau of Labor Statistics Producer Price Indexes

Figure 3 and Table 3 compare the GDP price deflator with the producer price indexes (PPIs) that the BLS publishes for military and analogous commercial systems. Like the BEA deflators, BLS price indexes are quality adjusted. The algorithms are described differently but are mathematically equivalent, and they employ the same general criteria (holding specification constant). However, there is no communication between the two organizations on how DoD procurement data are handled.

The bottom four PPIs in Figure 3 (solid lines other than for the GDP deflator) are relevant to defense, and the top three (dashed lines) are for analogous civilian goods included for comparison. The PPIs show substantially smaller growth rates for military aircraft engines and ships than for the analogous civilian goods. The disparity between the GDP and military growth rates is less for the PPIs than for the BEA national defense

deflators shown earlier. Aircraft engines have grown less, ships have grown about the same, and aerospace goods have grown more. (We are regarding the aerospace PPI as reflecting defense goods because BLS includes military communication and reconnaissance satellites as well as civilian-funded NASA space shuttles.) A now-discontinued PPI deflator for electronic computers during the 1991–2003 time period, normalized to 1991 = 100, indicates that computers experienced a huge average annual (quality adjusted) price decrease of 14.8% during this period (Table 3).

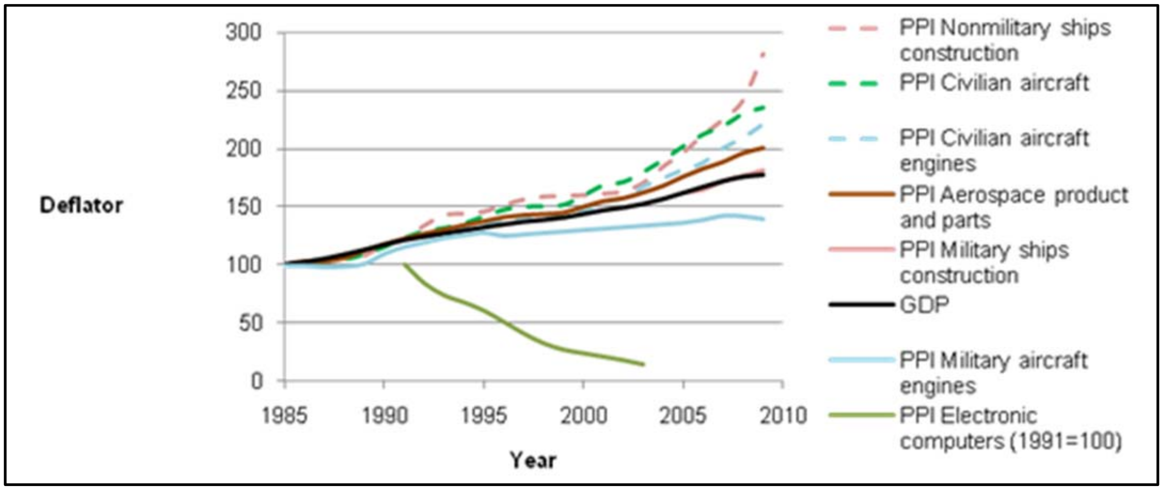

Figure 3. Producer Price Index Defense and Analogous Civilian Deflators
(BLS, n.d.)

Table 3. Comparison of Bureau of Labor Statistics Defense-Related Deflators

Deflator	Average Annual Growth Rate	Total Growth
PPI Non-military ship construction	4.4%	182%
PPI Civilian aircraft	3.6%	135%
PPI Civilian aircraft engines	3.4%	121%
PPI Aerospace product and parts	2.9%	101%
PPI Military ship construction	2.5%	82%
GDP	2.4%	78%
PPI Military aircraft engines	1.4%	40%
PPI Electronic computers (1991–2003)	-14.8%	-85%

As with the BEA deflators, some of the differences in growth rates might be due to the criteria and numerical methods for making quality adjustments.

Bureau of Economic Analysis and Bureau of Labor Statistics Price Indexes That Are Most Relevant for Defense

Figure 4 brings together the BEA and BLS PPI series that are most relevant to defense final products. There are major differences. The BEA indexes for defense aircraft, missiles, and electronics have grown much less than the GDP index. The aircraft index is

extremely far below the PPI index for civilian aircraft. The deflators for aerospace and military and ships are quite close to the GDP index.[12]

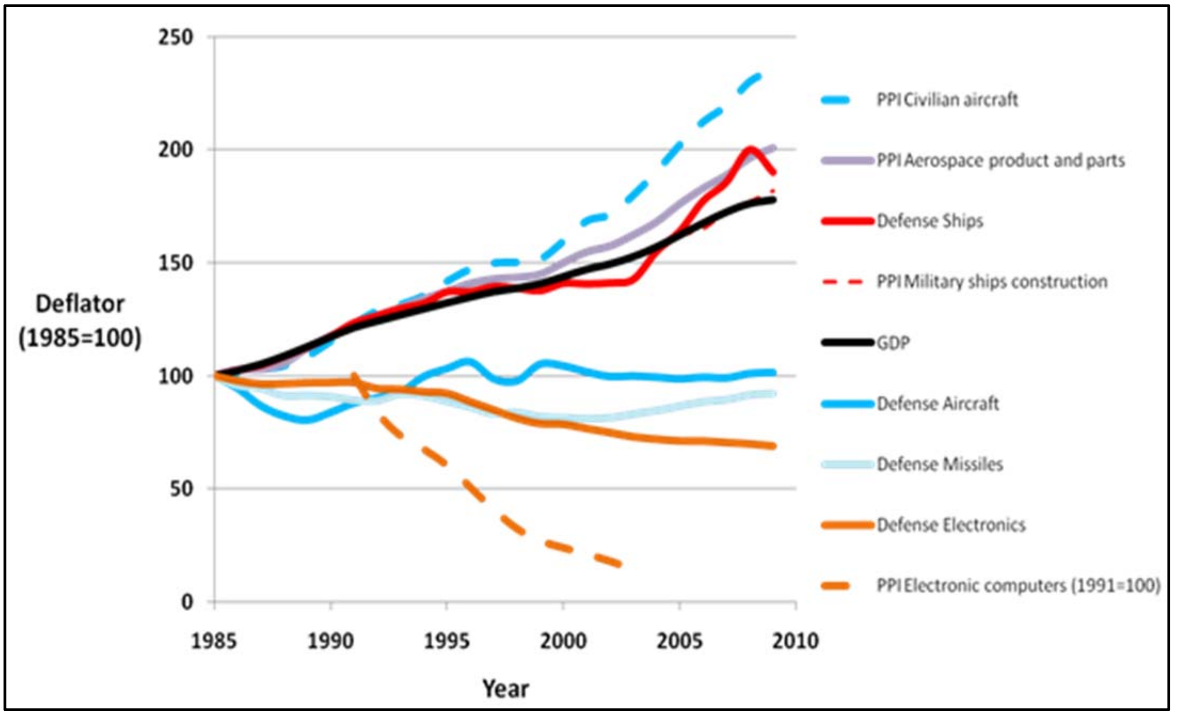

Figure 4. Defense and Producer Price Index Deflators Related to Defense

Conclusions From Retrospective Comparison of Alternative Deflators

The BEA national defense deflators seem most relevant to MDAPs because of the deflators' focus on defense-related products, but they are not entirely credible. The indexes for aircraft and missiles show much lower rates of increase than the GDP deflator and even much lower rates of increase than is measured for the commercial aircraft sector. As mentioned earlier, this might depend in part on how costs associated with improvements in capability are measured for purposes of making quality adjustments. Other indexes—for example, the national defense deflators for ships and vehicles and the PPI for military ships—have moved similarly to the GDP deflator.

The policy implication of these comparisons is that the difference in growth rates among the defense and defense-related indexes suggests that the DoD might obtain better measures of the real value of the overall MDAP budget by using sector-specific alternative price indexes instead of the GDP deflator. However, given the wide variability we have observed, our analysis fails to provide a clear picture. A better understanding of how the quality adjustments are made is needed.

Perhaps most important, neither the BEA nor the BLS provides price indexes that are derived from the prices of inputs used in the production of various types of MDAPs. The development and use of such indexes by organizations like NAVAIR reflects the indexes' superiority.

[12] The BLS does not publish indexes for military aircraft because there are not enough domestic producers to meet the BLS's standards for survey respondent confidentiality and statistical accuracy of the index.

Prospective Analysis: Success in Forecasting Inflation

Inflation predictions are useful in budget preparation only to the extent that they are accurate. The OMB forecasts the growth rates of the GDP deflator five years into the future, and Figure 5 shows the accuracy of these forecasts during the past 19 years. The initial forecast for 1991 in 1986, for example, was 2.3%, 1.5% lower than the most recent estimate of 3.8% in 2010.

Overall, the five-year forecasts seem fairly accurate. The number of overestimates and underestimates was about the same (10 vs. 9), and the absolute value of the yearly errors averaged only 0.8%. The overestimates were a bit larger than the underestimates, with maxima of 1.7% and 1.5%, respectively.

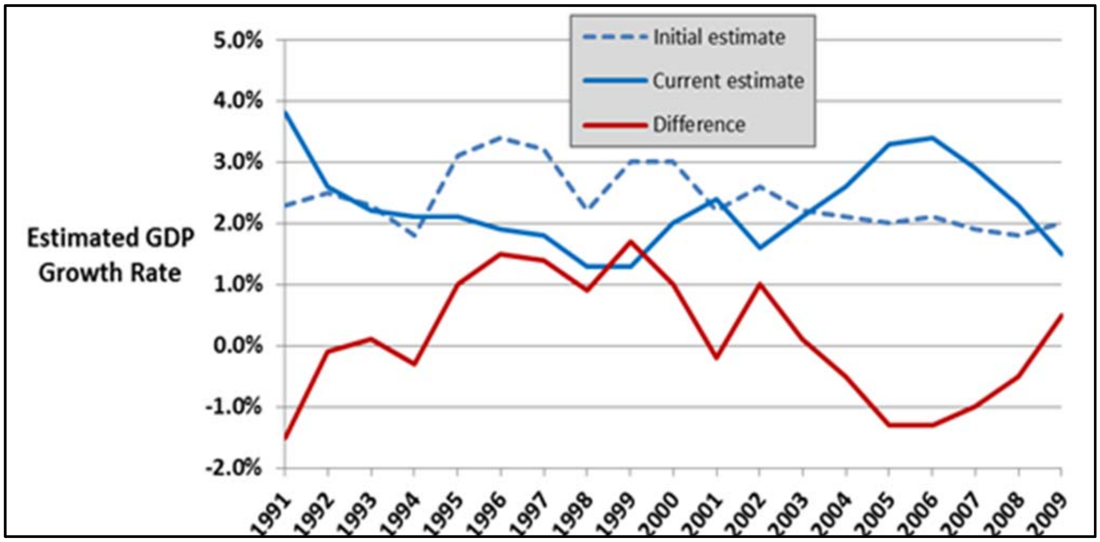

Figure 5. Accuracy of Predictions of the GDP Inflation Rate Five Years in the Future
(OUSD[C], 2010)

The estimates usually became more accurate as the year of execution approached, but they varied a good deal from year to year.

Because organizations like NAVAIR use inflation estimates developed by Global Insight, it would be useful to examine how accurate those estimates have been. Unfortunately, we do not have enough information at present to conduct such an analysis.

Assessment of Current Practices for Accounting for Inflation in the DoD

We previously mentioned that price indexes are used for two separate purposes in the DoD:

- budgeting for future spending, and
- measuring real cost growth in acquisition programs and identifying those programs whose real cost has grown enough to justify special management attention.

A key goal of budget development for particular programs is to allocate sufficient but not excessive funds for specific purposes. Budgeting for personnel, fuel, and health-related expenses draws on specific price indexes tailored for them and should meet the goal.

In the case of MDAPs, as long as programs follow the guidance to "reflect most likely or expected full costs," the goal should be met. However, if Comptroller rates are used to

estimate future price increases, in cases where those increases are expected to be greater or smaller than the Comptroller rates, programs will be underfunded or overfunded.

Program offices may have a tendency to over-estimate future price increases in order to build contingency reserves. The rationale for using specific price indexes should be clearly presented in budget submissions and should be subject to systematic review and approval at both the Service and OSD levels.

Our review of current practices in the section Current Practice for Incorporating Inflation Into Program Budgets and Cost Estimates for Major Defense Acquisition Programs indicates that program- or sector-specific price indexes based on input prices are used in shipbuilding, aviation, and space—areas in which Comptroller rates are often deemed to rise too slowly. The section Analysis of Alternative Deflators for MDAPs indicates that price increases for ground vehicles may have not differed greatly from the GDP deflator. In other words, current practices for procurement budgeting may reflect most likely or expected full costs fairly well overall.

Concerning the use of inflation escalation indexes for calculating real program cost growth, we discuss two possibilities:

- Adjusting for changes in the prices of inputs used for the particular program. This would absolve programs of responsibility for a category of cost increases that are largely beyond their control.
- Adjusting for price changes in the economy as a whole. This implies calculating real cost growth using the GDP deflator.

Use of program-specific indexes would be most consistent with the goal of identifying programs whose costs have risen for reasons other than higher input prices. However, program-specific input price indexes are not always available, and there is some virtue in the simplicity of using a single index to calculate real cost growth.

Using the GDP deflator to calculate real cost growth relative to the baseline can be justified. Real cost growth is consistently measured in terms of the cost of programs to the economy as a whole, not in terms of the physical resources used by the program. The current practice of using the best available information to prepare then-year dollar estimates means that program-specific input price increases that are expected to exceed general inflation are built into the baseline and do not count as cost growth. Unanticipated increases in input prices do contribute to measured cost growth and can contribute to Nunn-McCurdy breaches.

Concluding Observations and Suggestions

Observations

- There is no single price or inflation index that should be used for all purposes. The appropriate index depends on the mix of goods and services under consideration. If the context is measuring cost to the economy, a broad-index, like the GDP deflator, is appropriate. If the context is narrower, like predicting the cost of specific kinds of purchases, a more focused index is appropriate.
- The GDP deflator and the price indexes for particular sectors developed by the BEA and BLS are based on output prices. Although the DoD's purchases, including MDAPs, are outputs from the private sector, the cost-based nature of contract development supports the use of input-price-based indexes for MDAPs.

- Current DoD practices regarding the treatment of inflation support the DoD's needs for accurate budgeting and for calculating real program cost growth.
- Although the use of program-specific estimates of future input-price changes is the best way to ensure accurate budgeting for MDAPs, the estimates require systematic review at both the Service and OSD levels to resist a possible tendency to accumulate budget reserves in the guise of preparing for inflation.
- Guidance by the OUSD(C) on the use of its indexes to determine budgetary requirements and develop program cost estimates currently calls for budgets that (a) reflect most likely or full costs, and (b) use OUSD(C) indexes to determine price escalation. The guidance further states that the Comptroller's price indexes should be used to "determine the amount of price escalation for a procurement line item, major RDT&E system, or construction item over a given time period" (DoD, n.d.). This guidance is being revised to make it clear that most likely or expected full costs in then-year dollars should be used in budget preparation—even if this implies price increases different from those implied by Comptroller's indexes—and that Comptroller indexes must be used to convert then-year dollar values to constant-dollar values.
- The use of the GDP deflator to measure price increases for all DoD procurement programs is conceptually inappropriate. Healthcare, fuel and personnel have price indexes specific to them. This is not true for procurement. Empirically, the GDP deflator may be a reasonable proxy for procurement inflation overall, though this cannot be demonstrated. But it does not allow the DoD to capture differences between, for example, ships, aircraft, and vehicles. Individual organizations often develop their own approaches.
- This initial study does not indicate what alternative system- or category-specific indexes would provide better estimates of inflation for procuring the various types of systems. Government statistical organizations do not publish price indexes based on the prices of inputs to the production of systems, but they presumably could.
- Current practice does not appear consistent with either of the notions of constant prices noted at the start of the paper. By using tailored indexes for civilian personnel, military personnel, fuel, and medical care, it does not consistently calculate constant dollar costs in terms of resources foregone by the economy as a whole. By using the GDP deflator for procurement, it does not consistently calculate constant dollar costs in terms of the value of the resources acquired to the DoD.
- Some procurement price indexes, particularly the BEA national defense indexes for aviation and missiles, appear surprisingly low, with negligible growth since 1985. This may be due, at least in part, to the way that quality adjustments are identified and estimated.
- There has been little systematic tendency to either overestimate or underestimate inflation. Prediction of inflation five years in the future has been wrong by only about 0.8% on average.

Suggestions

- Complete the planned revision of OUSD(C) guidance.
- Investigate the feasibility of developing procurement price indexes tailored to different kinds of equipment. This would involve deeper analysis of the BEA and BLS for military systems, especially the use of indexes based on the prices of inputs to military systems.
- Compare the accuracy of inflation predictions promulgated by OMB and those developed by Global Insight.

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Political Connections of the Boards of Directors and Defense Contractors' Excessive Profits[1]

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Abstract

Despite the fast-growing interest in the research of *political connections* of either private-sector firms or states, most of the papers belong to the economics or public administration fields. There are few studies, if any, that look into the role of firms' political connections in the defense acquisition area. This paper makes an effort to bridge this gap by investigating the impact of political connections on the excessive profitability of defense contractors.

Wang and San Miguel (2012) documented that defense contractors earn excessive profits relative to their industry counterparts. This study extends Wang and San Miguel (2012) and examines whether defense contractors' political connections (as measured by the prior employment histories of the board directors) influence contractors' excessive profitability. We find that, in contrast to the prediction of "corruption hypothesis," the excessive profits are less (more) pronounced for those contractors with politically connected (non-connected) boards. This casts doubt on the preconceived notion that those politically connected board members are corrupt in nature; rather, our findings suggest that they may use their experience to serve a benevolent role to the public in keeping defense contractors from opportunistic profit-seeking behaviors that could reach or even cross the federal government's regulatory redline.

Introduction

Political connections[2] of either private-sector firms or public states has increasingly become a popular research topic among economists, business and public administration scholars, and political scientists. For example, in regard to states' political connection as measured by representation in the U.S. Congress, scholars have documented that per capita federal expenditures at the state level are positively related to per capita Senate representation, which gives rise to a small state advantage (Atlas, Gilligan, Hendershott, & Zupan, 1995). No similar advantage is found if data is restricted to earmarks secured in House appropriations bills[3] (Hoover & Pecorino, 2005; Knight, 2008). This seems to suggest that political connection does matter from a state's perspective.

Naturally, a similar research question exists for private-sector firms: that is, do politically connected private-sector firms derive economic benefits from such a relation? Most studies intended to answer this question somewhat support this conjecture. For instance, Goldman, Rocholl, and So (2009) demonstrated that the market responds positively (i.e., a positive abnormal stock return is observed) to the announcement of the

[1] JEL Classifications: G38, H57, M48.
[2] There is no consensus regarding the definition of *political connection*. Definitions vary with specific studies.
[3] Note that each state has two senators, regardless of the population of the state. The representation in the U.S. House, however, is based on state population.

nomination of a board member who is politically connected from his or her prior employment history in the federal government, military services, or as a former representative of the U.S. Congress. Duchin and Sosyura (in press) investigated application data for Troubled Asset Relief Program (TARP) funds and found that those firm applicants with political connections[4] were more likely to be funded. Correia (2012) found that for firms with irregular accounting practices, those with political connections are less likely to become the target of Securities and Exchange Commission (SEC) investigation, and if they are indeed investigated, they face lower penalties on average than non-connected firms. Khwaja and Mian (2005) used Pakistan banks' corporate lending data to show the rent-seeking behavior of politically connected firms. In particular, they found that "political firms borrow 45 percent more and have 50 percent higher default rates. Such preferential treatment occurs exclusively in government banks—private banks provide no political favors" (p. 1371). It is also worth mentioning that these studies not only document the real impacts of political connections, but they also share a common theme suggesting that political connections are a source of corruption and underlie various rent-seeking behaviors. Simply put, political connections matter in a negative way.

Despite the fast-growing interest in the research of political connections, most of the papers belong to the economics, political science, or public administration field. There are few studies, if any, that look into the role of firms' political connection in the defense acquisition area, which provides another proof of the alleged disciplinary disconnect[5] that has existed for a long time.

The objective of this paper is twofold. First, we attempt to bridge the gap that exists between defense acquisition study and other relevant research fields, such as economics and public administration. As observed by many academicians and practitioners, such a disengagement of defense acquisition research (with other fields) is both unfortunate and unjustified. The society will be better served if such a disconnection is mitigated. Toward this goal, we build on the extant literature and aim to investigate the impact of political connections (an established concept in non-defense research) on a very important topic in defense acquisition, that is, the excessive profitability of defense contractors. Specifically, Wang and San Miguel (2012) documented that defense contractors earn excessive profits relative to their industry counterparts. This study extends Wang and San Miguel (2012) and examines whether defense contractors' political connections (as measured by the prior employment histories of the board directors) influence contractors' excessive profitability.

Our second goal is to test the "corruption hypothesis of political connections" that has been suggested by existing literature in a very particular and essential setting, that is, the nation's biggest defense contractors' excessive profitability. If the results support the

[4] The definition of political connection in Duchin and Sosyura (2012) takes several forms, including lobbying, campaign contributions, and employment history of directors.

[5] Such disconnect exists between public administration and military administration (Albano, Snider, & Thai, 2012), and more generally, between economics and military-related research (Rogerson, 1994). Rogerson (1994) stated, "Defense procurement is unique among regulated industries in the United States in that economists have played virtually no role in helping shape its regulatory practices and institutions. Perhaps this is due to the barrier to entry created by the need to first learn about procurement practices or to a lingering distaste for military matters among academics. Whatever the reason, this lack of economic input is unfortunate, because many of the regulatory and policy issues in defense procurement involve the types of incentive issues that economists are very good at analyzing. My own hope is that economists are on their way to colonizing this new policy frontier and that some of the ideas discussed in this article will play a role in shaping policy debates over the next decade" (p. 87).

corruption story, then political connections would become a very serious concern of policy-makers because defense spending is a substantive portion of government expenditures. On the other hand, if such a conjecture is not grounded, what are the findings and what is the explanation?

The remainder of the paper is organized as follows. The section titled Sample describes our sample. The section titled Measuring Political Connections and Hypotheses Development introduces the measure of political connections, followed by the development of hypotheses on the relationship between excessive profitability and political connections, based on extant literature and observations. Empirical results and findings are in the section titled Empirical Results and Findings. The final section concludes the paper.

Sample

We start with the same sample used in Wang and San Miguel (2012). Specifically, they use fedspending.org as the data source to identify the top 500 recipients of defense contracts for 2008. Out of these top 500 firms, 112 are traded on public stock exchanges. These 112 public firms became the main sample of their analyses. Our sample is a reduced version of Wang and San Miguel (2012) in that we delete 16 firms that are missing from the Corporate Library database, which we use to identify the political connections of each firm's board members. Table 1 lists the name, dollar awarded, rank, stock ticker, SIC code, and public stock exchange code for these 96 public firms.

Table 1. Firms in The Main Sample: 96 Public U.S. Firms From the 2008 Top 500 list

Company Name	Contracted_dollars_2008	Rank	Stock Ticker	SIC	EXCHG (11=NYSE, 12=AMEX, 14=NASDAQ)
LOCKHEED MARTIN CORP	$29,363,894,334	1	LMT	3760	11
NORTHROP GRUMMAN CORP.	$23,436,442,251	2	NOC	3812	11
BOEING CO.	$21,838,400,709	3	BA	3721	11
RAYTHEON CO.	$13,593,610,345	6	RTN	3812	11
GENERAL DYNAMICS CORP.	$13,490,652,077	7	GD	3790	11
UNITED TECHNOLOGIES CORP.	$8,283,275,612	8	UTX	3720	11
L-3 COMMUNICATIONS HOLDINGS	$6,675,712,135	9	LLL	3663	11
KBR INC.	$5,997,147,425	10	KBR	1623	11
NAVISTAR INTERNATIONAL CORPORATION	$4,761,740,206	11	NAV	3711	11
ITT CORPORATION	$4,355,423,578	13	ITT	3812	11
SCIENCE APPLICATIONS INTL CORP	$3,885,932,047	14	SAI	7373	11
GENERAL ELECTRIC COMPANY	$3,518,136,891	15	GE	9997	11
COMPUTER SCIENCES CORP.	$3,230,197,590	16	CSC	7370	11
HUMANA, INC.	$2,952,008,623	18	HUM	6324	11
TEXTRON, INC.	$2,827,900,303	19	TXT	3721	11
HEALTH NET, INC	$2,438,349,117	21	HNT	6324	11
URS CORP.	$2,402,033,979	22	URS	8711	11
HEWLETT-PACKARD CO.	$1,938,638,634	26	HPQ	3570	11

ALLIANT TECHSYSTEMS, INC.	$1,928,045,694	27	ATK	3480	11
OSHKOSH TRUCK CORP.	$1,863,726,822	30	OSK	3711	11
HARRIS CORP.	$1,841,470,263	31	HRS	3663	11
HONEYWELL, INC.	$1,721,547,997	33	HON	3728	11
FORCE PROTECTION INDUSTRIES, (INC)	$1,360,427,189	36	FRPT	3790	14
CACI INTERNATIONAL INC	$1,324,104,004	37	CACI	7373	11
AMERISOURCE BERGEN CORP	$1,298,059,841	38	ABC	5122	11
ROCKWELL COLLINS	$1,290,813,364	39	COL	3728	11
SHAW GROUP, INC.	$1,162,267,243	40	SHAW	8711	11
VALERO ENERGY CORPORATION	$1,043,869,551	43	VLO	2911	11
JACOBS ENGINEERING GROUP INC	$951,295,410	45	JEC	1600	11
VSE CORP.	$910,970,473	47	VSEC	8711	14
MCKESSON CORPORATION	$903,799,326	48	MCK	5122	11
CARDINAL HEALTH INC	$856,333,988	50	CAH	5122	11
DELL COMPUTER CORPORATION	$852,813,703	51	DELL	3571	14
EXXON MOBIL CORP.	$836,548,150	52	XOM	2911	11
MANTECH INTERNATIONAL CORP	$655,579,972	61	MANT	7373	14
FLIR SYSTEMS, INC	$507,944,847	71	FLIR	3812	14
GOODRICH CORPORATION	$487,753,671	73	GR	3728	11
TETRA TECH, INC.	$472,960,770	77	TTEK	8711	14
IBM CORP.	$438,446,918	81	IBM	7370	11
PERINI CORP.	$436,363,793	82	TPC	1540	11
FLUOR CORP.	$430,878,065	84	FLR	1600	11
CERADYNE INC	$417,616,849	86	CRDN	3290	14
AECOM TECHNOLOGY CORPORATION	$380,250,228	91	ACM	8711	11
AT&T INC.	$371,099,463	95	T	4813	11
KRAFT FOODS INC	$367,840,952	97	KFT	2000	11
OWENS & MINOR INC	$365,861,498	99	OMI	5047	11
CUBIC CORP.	$354,623,567	102	CUB	3812	11
GREAT LAKES DREDGE & DOCK CORPORATION	$324,475,211	113	GLDD	1600	14
CATERPILLAR, INC.	$323,676,276	114	CAT	3531	11
PROCTER & GAMBLE CO.	$321,983,149	115	PG	2840	11
TYSON FOODS INC	$319,486,334	117	TSN	2011	11
VERIZON COMMUNICATIONS	$319,365,283	118	VZ	4812	11
CHEVRONTEXACO CORPORATION	$310,558,853	122	CVX	2911	11
SRA INTERNATIONAL, INC.	$297,913,799	128	SRX	7370	11
GRANITE CONSTRUCTION CO.	$292,263,100	131	GVA	1600	11
ACCENTURE	$288,517,607	132	ACN	8742	11
JOHNSON CONTROLS, INC.	$285,123,825	134	JCI	2531	11
EXPRESS SCRIPTS	$215,750,049	162	ESRX	6411	14

CONOCOPHILLIPS	$206,348,789	167	COP	2911	11
TYCO INTERNATIONAL LTD	$202,567,751	172	TYC	9997	11
COMTECH TELECOMMUNICATIONS CORP.	$202,082,670	173	CMTL	3663	14
GENERAL MILLS, INC.	$200,017,932	176	GIS	2040	11
TESORO HAWAII CORPORATION	$199,447,230	177	TSO	2911	11
AEROVIRONMENT INC	$192,462,098	182	AVAV	3721	14
AAR CORP.	$187,717,969	187	AIR	5080	11
SYSCO CORPORATION	$179,074,006	195	SYY	5140	11
REFINERY HOLDING COMPANY L P	$177,749,226	198	WNR	2911	11
DEERE & CO.	$164,340,456	206	DE	3523	11
VIASAT, INC	$156,815,300	217	VSAT	3663	14
ORBITAL SCIENCES CORP.	$153,884,356	223	ORB	3760	11
PEPSICO INC	$149,527,183	231	PEP	2080	11
UNISYS	$142,990,124	239	UIS	7373	11
BALL CORP	$131,696,095	259	BLL	3411	11
CONAGRA, INC.	$125,264,234	270	CAG	2000	11
ORACLE CORP.	$122,646,803	274	ORCL	7372	14
GENERAL MOTORS CORP.	$120,929,817	279	GM	3711	11
EATON CORP.	$117,792,917	286	ETN	3620	11
UNILEVER NV	$112,089,508	292	UL	2000	11
MOOG, INC.	$111,608,841	293	MOG.A	3728	11
ALON USA L.P.	$111,102,800	296	ALJ	2911	11
COCA-COLA ENTERPRISES INC	$93,991,833	343	CCE	2086	11
XEROX CORP.	$91,275,424	356	XRX	3577	11
JOHNSON & JOHNSON	$89,990,235	363	JNJ	2834	11
CAMPBELL SOUP CO.	$88,645,010	367	CPB	2030	11
INTERMEC CORPORATION	$83,566,808	388	IN	3577	11
CAE CORP	$83,563,697	389	CAE	3690	11
DEL MONTE FOODS COMPANY	$77,962,809	419	DLM	2000	11
AMERICAN SCIENCE AND ENGRG	$76,545,302	429	ASEI	3844	14
MICHAEL BAKER CORP.	$74,263,592	437	BKR	8711	12
KIMBERLY-CLARK CORP.	$69,832,351	454	KMB	2621	11
ESTERLINE TECHNOLOGIES CORP	$68,716,933	462	ESL	3823	11
INTEGRAL SYSTEMS, INC.	$67,261,245	473	ISYS	7373	14
MINE SAFETY APPLIANCES CO.	$67,166,647	474	MSA	3842	11
WORLD FUEL SERVICE CORP.	$66,258,375	478	INT	5172	11
SARA LEE CORPORATION	$65,361,053	482	SLE	2000	11
WILLIAMS COMPANIES INC	$65,024,852	483	WMB	4922	11
HORIZON LINES LLC	$65,008,856	484	HRZ	4400	11

Table1 shows that most of the firms in our sample are listed on the NYSE or NASDAQ, indicating that big defense contractors are likely to be established companies. For

each of the 96 firms, we use their stock ticker to map into the Compustat database and extract various accounting variables across a three-year range of 2007–2009. Note that our base year is 2008. The reason we include two additional years of data (i.e., 2007, one year prior, and 2009, one year after) is to expand the sample size and simultaneously ensure that the status of the top 500 defense contractors in 2008, as well as the political connections of the board members in 2008, can be assumed to be stationary and be passed onto 2007 and 2009 for the same firm, due to a short elapse of time. Expanding our sample to a three-year range yields a total of 276 firm-years, with 93 each for 2007 and 2009 and 90 for 2008. Following Wang and San Miguel (2012), we denote the excessive profit of a particular firm-year as the difference between this firm-year's return on assets (ROA)[6] and the ROA of an "industry-year-size" matched benchmark firm that is not on the 112-firm list.[7]

Table 2 presents basic statistics of descriptive accounting measures for the 90 sample firms in Fiscal Year 2008.[8] In particular, we report total assets, total sales (revenue), dollar awarded as percentage of revenue, and excessive profit as measured by the matched ROA. The mean values of total assets and total revenue were $35 billion and $33 billion, respectively. The government contracts contributed about 18% of these firms' 2008 revenue on average.[9] Overall, these firms earned an excessive ROA of 3%, which is statistically significant at a 5% significance level, confirming Wang and San Miguel's (2012) findings that top defense contractors receive excessive profits relative to their industry peers.

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[6] To keep the paper concise, we exclusively use ROA as the profitability metric in this study. Other alternative profit measures yield similar results.

[7] "The benchmark firm-year is selected based on a three-dimension match on industry, year and size. Specifically, we go to the same industry-year where industry membership is defined as four-digit SIC codes, and identify the non-defense (i.e., not on our 112-firm list) firm that has the best size match with our defense firm-year. The difference between the profit of the firm-year investigated and the profit of the benchmark firm-year will be the measure of 'excessive profit'" (Wang & San Miguel, 2012, p. 397).

[8] We lost six firms for Year 2008 due to missing data from Compustat.

[9] A concern that has been raised here is that a significant portion of our sample firms may have much lower than 18% of their total revenue that is attributable to DoD contracts, and hence, are not really "defense contractors" as the term is generally understood. Consequently, if Sara Lee had only 1% of 2008 sales from defense contracts, one cannot attribute much, if any, of Sara Lee's excessive profits to its defense contracts. We provide a few arguments to address the aforementioned concern. First, our sample focuses on DoD contractors, a much broader concept than a few prominent major weapon manufacturers. In that regard, an average 18% revenue from DoD is a reasonably decent number. Second, the central metric of our analysis is the excessive profit, and because profit is only a small portion of revenue, a relatively small percentage of DoD revenue could have a much larger impact on profit if firms do derive larger profits from DoD contracts than they can generate from their non-DoD business. Third, it is worth mentioning that the specific concern as expressed by using the Sara Lee example above is already addressed, if not completely removed, by our definition of the three-way industry-year-size matched excessive profit measure. In particular, if Sara Lee had a super good year for whatever reason that is non-DoD related, we expect that its benchmark firm, i.e., the firm that is in the same industry and has similar size (but without federal contracts), would also be impacted in a similar way and display a superior profit likewise in the same year. Hence, the excessive profit of Sara Lee, which is the difference between Sara Lee's profit and its benchmark firm's profit, would be only attributable to the fact that Sara Lee has DoD contracts while its benchmark firm has not. Last but not least, despite that we believe our current full-sample approach is sound, we nevertheless proceed to perform a robustness analysis, which only includes the subsample that consists of only those firms with at least 25% of total revenue generated from DoD contracts. Untabulated results show that all our findings are intact.

Table 2. The Basic Statistics of 90 Sample Firms in Year 2008

	Mean	Median	Min	Max	Std Dev
Total Assets (millions)	34,962	7,242	147	797,769	94,895
Total Sales (millions)	32,656	12,542	160	425,071	59,570
Dollar Awarded as Percent of Sales (%)	17.56	6	0.06	103.00	22.79
Excessive ROA	0.03	0.02	-0.18	0.32	0.10

Measuring Political Connections and Hypotheses Development

Measuring Political Connections

There is no unanimously agreed-upon definition of the term *political connection*.[10] Scholars have used various forms of concepts in different research settings. For example, Mara Faccio, in a series of solo and coauthored papers,[11] defined a firm's political connection as follows: "A company is defined as being connected with a politician if at least one of its largest shareholders (anyone controlling at least 10 percent of voting shares) or one of its top officers (CEO, president, vice-president, chairman, or secretary) is a member of parliament, a minister, or is closely related to a top politician or party" (Faccio, 2006, p. 369). This definition by Faccio is not appropriate for any U.S.-based study because U.S. regulations pretty much rule out the possibility of anybody simultaneously serving a high-rank public service role and a top executive role in a private-sector firm. In the United States, if a present executive of a private-sector firm is appointed as a high-rank government official, he or she must quit his or her current job. As a testimony of this fact, Faccio (2010) found that under her definition, only 13 out of the 6,007 U.S. firms in the Worldscope database can be labeled as "politically connected firms." In short, this first definition applies more to international countries, such as Indonesia, Malaysia, or Italy.

The second definition of *political connection* focuses on campaign contributions and lobbying activities. For instance, Correia (2012) found that firms' political connections established by contributions to congressmen and by lobbying the SEC reduce those firms' enforcement costs by the SEC. Specifically, those firms are less likely to be investigated by the SEC, and even if they are investigated, the average penalty is lower for them. Other studies that adopted this definition include Roberts (1990), Kroszner and Stratmann (1998), and Ang and Boyer (2000). The problem with this definition is the low explanatory power. For instance, Goldman et al. (2009) found that controlling industry effect significantly reduces the explanatory power of campaign donation. Moreover, Jayachandran (2006) questioned the causal effect of firms' donations on firm value. To recap, the second definition, based on campaign donation or lobbying expenditure, at most provides a noisy measure of political connection.

The third alternative definition of *political connection* is derived from board directors' prior employment history in the federal government, including in the legislative, executive, and judiciary branches, and in the military Services. Since in the U.S., congressmen, government executives, and military generals are allowed to serve on the boards of private-sector firms after their retirement from public service (and they frequently do so), firms'

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[10] From this point on, we restrict our attention on political connections to private-sector firms rather than public states. One example of a public state's political connection was introduced previously.
[11] See Faccio (2006), Faccio (2010), Faccio, Masulis, and McConnell (2006), and Chaney, Faccio, and Parsley (2011).

political connections through board members receive substantial attention. Many U.S.-based studies follow the suit of this particular definition. To name a few, Agrawal and Knoeber (2001) found that firms for which politics plays a more important role tend to be more "politically connected" (i.e., they tend to have more politically experienced directors on their boards). Goldman et al. (2009) showed the market value relevance of the addition of a newly appointed, politically connected board member. Moreover, they differentiate between political connections to the Republican versus Democratic parties and provide evidence that the market values of these two different types of politically connected firms responded differently to George W. Bush's 2000 presidential win.

Since our sample is strictly U.S. based, it is natural to follow the third definition of *political connection*. Specifically, we use the 2008 Directorships database that is provided by Corporate Library LLC. In this annual directorship dataset, Corporate Library records each individual director's information through compiling data from firms' publicly disclosed proxy statements. One key field in this database is a director's biography, including detailed employment history. We use a series of keywords to search each individual director's biography statement and identify whether this particular director is politically connected. The keywords we use are comprehensive to ensure a maximum catch of politically connected directors. The complete list of our search keywords follows: *senator*, *congressman*, *congresswoman*, *congress*, *representative*, *federal*, *secretary*, *admiral*, *general*, *army*, *navy*, *air force*, *department of defense*, *DoD*, *commissioner*, *ambassador*, *administrator*, *attorney general*, *governor*, *director*, *council*.

We apply this keyword search to the biography statement as of Year 2008 for each director who sits on the board of any of our 96 sample firms. Once we find a "hit" of a keyword, we read the biography and make sure this particular director is correctly flagged as one who is politically connected.[12] At Year 2008, our 96 sample firms have 989 directors in total, indicating an average board size of 10.3 directors. Out of these 989 directors, 923 are unique individuals, of which 157 are identified as politically connected directors. Put simply, 17% of the directors have prior employment history with the federal government or military Services. The data also indicate that 77 out of 96 firms have at least one politically connected director on their board; that is, 80% of our top defense contractors have some degree of political connection through the board of directors. To get a benchmark sense, it is worth mentioning that Goldman et al. (2009), using a very similar definition of *political connection* as our study, documented that at Year 2000, 153 of the S&P 500 companies (i.e., 31%) had at least one board member with a political connection. Therefore, the main message is that top defense contractors are much more likely to have a politically connected board than non-contractor firms.

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[12] An example of a politically connected director's profile is General John M. Shalikashvili, who served as a board director of L-3 Communications Holdings, Inc., at Year 2008. The following excerpt was from the company's proxy statement: "General John M. Shalikashvili, director since August 1998 and member of the Compensation and Nominating/Corporate Governance Committees. General Shalikashvili (U.S. Army—Ret.) is an independent consultant and a Visiting Professor at Stanford University. General Shalikashvili was the senior officer of the United States military and principal military advisor to the President of the United States, the Secretary of Defense and the National Security Council when he served as the thirteenth Chairman of the Joint Chiefs of Staff, Department of Defense, for two terms from 1993 to 1997. Prior to his tenure as Chairman of the Joint Chiefs of Staff, he served as the Commander in Chief of all United States forces in Europe and as NATO's tenth Supreme Allied Commander, Europe (SACEUR). He has also served in a variety of command and staff positions in the continental United States, Alaska, Belgium, Germany, Italy, Korea, Turkey and Vietnam."

Hypotheses Development

In this subsection, we derive alternative hypotheses on the relationship between defense contractors' excessive profitability and their political connections, based on extant literature and observations. Most of the prior literature suggests the "corruption" role of political connection (i.e., the firms with political connections opportunistically take advantage of this favorable relation and inappropriately derive private benefits for the firm at the sacrifice of social welfare). For example, Duchin and Sosyura (in press) found that politically connected firms are more likely to get TARP funds, yet their performance was inferior to that of unconnected firms. This clearly indicates that political connection is a source of "corruption" and "inefficiency." Correia (2012) presented evidence showing that firms use their political influence to avoid the scrutiny of the SEC or mitigate the punitive damage in the case of financial reporting irregularity. Faccio et al. (2006) analyzed a unique dataset that covers 35 countries during 1997–2002 and found that those politically connected firms are far more likely to be bailed out during financial distress than non-connected firms in a similar economic crisis. Moreover, after bailout, those firms with political connections significantly underperform unconnected firms. Chaney et al. (2011) documented that politically connected firms have poorer earnings quality than their non-connected counterparts. All of the studies mentioned previously collectively convey a consistent message: that is, political connection is associated with various rent-seeking behaviors. Applying this corruption proposition of political connections to the defense contractors' excessive profit, we have the following hypothesis:

> Hypothesis (H): The defense contractors' excessive profitability is more pronounced for those with political connections. Non-connected firms should exhibit a less excessive profit.

While this hypothesis sounds like a reasonable conjecture given all evidence in the extant literature, an alternative hypothesis nevertheless could exist. In particular, if defense contractors, a unique subset of universal firms, have different and non-opportunistic motives for establishing political connections, then the story could be very different. Given the unique nature of the defense procurement business, it is quite likely that commonality may not prevail here. For instance, one distinctive feature of defense-related business is the complexity of regulation, which often requires substantive professional and inside knowledge to truly understand. The Federal Acquisition Regulation (FAR) alone consists of thousands of pages full of government-specific terminologies. Further, a firm that is doing business with the Department of Defense (DoD) is under the scrutiny of various government agencies, such as the Government Accountability Office (GAO), the Defense Contract Audit Agency (DCAA), and others. There is a high cost of non-compliance. A defense contractor that is found to engage in misconduct could face various penalties including settlement with fine, civil or criminal investigation, suspension, or even debarment. If defense contractors believe that these redlines are costly to cross, they may have incentives to hire the best talent with professional and institutional knowledge to help them avoid such behavior. For example, a March 22, 1991, article in *The Wall Street Journal,* titled "Northrop Nominates Three for Its Board," reported that

> The nominees are Joseph A. Califano Jr., 59 years old, a Washington attorney and former Secretary of Health, Education and Welfare under President Jimmy Carter; Jack Edwards, 62, a Washington lawyer and formerly the ranking Republican congressman on the Defense Appropriations Subcommittee; and retired Gen. John T. Chain Jr., 56, a 35-year Air Force veteran who this year retired as commander-in-chief of the Strategic Air

Command to become executive vice president of operations of Burlington Northern Railroad Co.

A company spokesman said in the news announcement, “[These] board members are chosen for the breadth of their experience and counsel” (“Northrop Nominates,” 1991). Moreover, Kent Kresa, then Northrop president and chief executive officer, further commented, “These men bring to Northrop unsurpassed experience and knowledge in their own fields, and a diversity that will serve us well as we shape the company to match the changes taking place in the country and the world” (“Northrop Nominates,” 1991). Note that two of the individuals are attorneys and all three of them had extensive and high-profile government or military experiences. Their expertise and experience, if used under good intention, would greatly help Northrop comply with the regulatory and executive rules. Recognizing this potential competing theory, we offer the following alternative hypothesis:

> Alternative Hypothesis (AH): The defense contractors’ excessive profitability is less pronounced for those with political connections. Non-connected firms should exhibit a more excessive profit.

Both H and AH have reasonable justifications. Which one is factually supported? The next section empirically investigates this issue.

Empirical Results and Findings

Univariate Analysis

We first report the univariate statistics of key variables. Recall from the Sample section that we have 276 firm-years in a three-year range of 2007–2009. We classify each of these 276 firm-years into one of the two mutually exclusive groups. The first group, labeled as “non-politically connected” firms, consists of all firm-years for which none of a firm’s Year-2008 board members had political connection through his or her prior employment. All of the other firm-years that are not in the first group had at least one of the firm’s board members being classified as a “politically connected director” and hence belong to the second group called “politically connected” firms. Out of the 276 firm-years, 54 are politically non-connected and 222 are connected.

Table 3. The Univariate Comparison of Key Variables Between Politically Connected and Non-Connected Firm-Years

Group	N	Variable	Mean	Std Dev
Politically Non-Connected	54	Total Assets (millions)	13,535	23,945
		Total Sales (millions)	22,754	30,769
		Dollar awarded as percent of sales (%)	8.52	11.73
		Excessive ROA	0.04	0.09
Politically Connected	222	Total Assets (millions)	41,339	103,331
		Total Sales (millions)	33,060	56,377
		Dollar awarded as percent of sales (%)	21.59	28.00
		Excessive ROA	0.01	0.08

We have several immediate observations from Table 3. First, politically connected defense contracting firms are much bigger than non-connected ones. Measured by assets (revenue), a typical politically connected firm is three (one-and-a-half) times as big as a typical non-connected firm. Second, defense contracts account for a much bigger portion of total revenue for politically connected contractors than for non-connected ones. Specifically, about 21.6% (as opposed to 8.5%) of total revenue is generated by defense contracts for politically connected firms (as opposed to non-connected firms). This particular evidence is consistent with Agrawal and Knoeber (2001), who found that for those firms in which sales to government plays a more important role, the presence of politically connected directors on the board is greater as well. It is also in line with the finding of Goldman, Rocholl & So (in press) that political connections affect the allocation of procurement contracts. Nevertheless, we would like to stress that just because there is a positive association between the political connection and the defense contract dollar as a percentage of revenue does not necessarily indicate a rent-seeking or corruption story. It is plausible that the hiring of political experience is well intentioned and that those valuable experiences are legitimately used to compete for government contracts in a lawful and ethical way. Last but not least, a univariate comparison on excessive profits (as measured by excessive ROA) between politically connected and non-connected groups demonstrates that the former displays a much less pronounced excessive profit than the latter (4% versus 1%). This suggests that preliminary evidence casts doubt on the corruption (or rent-seeking) hypothesis and favors our alternative hypothesis, which supports the non-opportunistic motives for establishing

political connections. That said, a more sophisticated approach (beyond univariate analysis) is needed to provide more convincing evidence.

Multivariate Analysis

In this subsection, we use a multivariate regression method to examine whether the evidence against the corruption hypothesis in a univariate context persists in a multivariate setting. Put another way, we want to inspect whether our preliminary finding based on a univariate relation is robust to controlling all known determinants of defense contractors' excessive profits. Needless to say, our dependent variable (i.e., the left-hand-side variable) is the firms' excessive profits, and our main variable of interest on the right-hand side is the firms' political connections. To ensure that the impact of political connection on excessive profit is incremental to the effects of all the other known determinants of excessive profits, we need to include a set of control variables on the right-hand side of the regression. Wang and San Miguel (2012), a recent work on defense contractors' excessive profits, provided us with a reference for that purpose.

Wang and San Miguel (2012) not only confirmed the existence of defense contractors' excessive profits but also they document two determinants of excessive profitability. In particular, by showing defense contractors' excessive profits being more pronounced after 1992, they argued that the post-1992 significant industry consolidation improved the bargaining power of the newly combined firms and, in turn, amplified these firms' profitability. This basically indicates that the degree of industry concentration is a key determinant of excessive profit. The second determinant documented by Wang and San Miguel (2012) is the quality of corporate governance, as measured by the duality of the chief executive officer (CEO) and the chairman of the board. The main justification behind this relation is that poorer corporate governance exacerbates firms' rent-seeking behavior that arises from substantial information asymmetry between the government and defense contractors.

In addition to the two determinants from Wang and San Miguel (2012), that is, the degree of industry concentration and the quality of corporate governance, we also include the size of the firm as a third control variable. There are two reasons for doing that. First, firm size is a commonly used control variable in empirical corporate finance studies. The justification is that size is such a "composite" variable that incorporates so many characteristics and information that for any particular study, it is a noisy measure of the particular variable of interest, yet a universal and perfect control variable that is nice to be included on the right-hand side. Second, Table 3 clearly shows that there is a negative correlation between the size of the firm and the firm's excessive profitability, and a positive correlation between the size of the firm and the firm's political connection; that is, smaller defense contractors tend to exhibit more pronounced excessive profits and less political connection relative to bigger ones. Hence, it is appropriate to include the size of the firm as a control to avoid the potential correlated omitted variable problem that could damage the statistical inferences of the multivariate regression model.

So the multivariate regression includes three control variables besides the variable of interest (i.e., political connection). The dependent variable is, of course, the excessive profits as defined by a three-way industry-year-size matched excessive ROA,[13] as elaborated in Wang and San Miguel (2012). The empirical proxies for the three control variables are as follows: we use a logarithm of total revenue as "firm size," the duality of CEO and chairman of the board as a binary measure of "corporate governance," and the

[13] Where industry is defined as four-digit SIC code, size is defined as total assets. Alternative definitions yield similar results.

percentage of industry revenue represented by the largest four firms within the industry as a gauge of the degree of industry concentration. Same as Wang and San Miguel (2012), we extract total revenue from Compustat and assess whether the CEO is also the chairman of the board from firms' proxy statements. Regarding the proxy for the degree of industry concentration, we use the Year-2007 "Concentration Ratios" published by the Census Bureau of the U.S. Department of Commerce. Table 4 reports the regression results.

Table 4. Multivariate Regression: The Excessive Profitability and Firms' Political Connections

Independent Variables	Dependent Variable: Industry-Year-Size Matched Excessive ROA Excessive ROA= a+ b*political connection +c*corporate governance+ d*firm size+ e*industry concentration	
	Political Connection measured by a dummy indicator	Political Connection measured by the percent of politically connected directors in the Board
Intercept	0.05	0.04
Political Connection (t-value)	-0.04 **(0.01)***	-0.07 **(0.04)**
CEO-Chairman Duality Dummy (t-value)	0.01 (0.29)	0.01 (0.31)
Firm Size (t-value)	-0.08 **(0.05)**	-0.08 **(0.05)**
Industry Concentration (p-value)	0.10 **(0.03)**	0.11 **(0.02)**

Notes. * indicates 10% significance level, ** indicates 5% significance level, *** indicates 1% significance level; CEO-Chairman dummy takes value of one if the CEO is also the chairman; Firm size is defined as logarithm of total revenue; Industry concentration is defined as the percentage of industry revenue represented by the largest four companies within the industry.

Table 4 shows that excessive profitability is lower for those firms with political connections, regardless of whether political connection is measured as a binary indicator variable or as the percentage of politically connected directors on the board. The magnitude of the impact is both statistically and economically significant. Moreover, this result holds after controlling other known determinants of excessive profits. The signs of all the control variables are as expected, and the magnitudes of the coefficients of control variables are significant except for the corporate governance proxy. Overall, the multivariate regression results reject the corruption or rent-seeking hypothesis and suggest a non-opportunistic motive of establishing political connections through board directors' prior experience.

Conclusion

Using a slightly reduced sample from the one used by Wang and San Miguel (2012), we investigate the impact of political connections on excessive profits of defense contractors. We measure political connections by searching the biographies of board directors in the firms' proxy statements. We find that defense contractors are more likely to have politically connected director(s) in their board; moreover, among defense contractors, those with a politically connected board tend to have a higher percentage of revenue from defense contracts than those without political connection. While the evidence may suggest that defense contractors have stronger incentives to establish political connections through

the recruitment of board directors, and those directors may indeed help the firm to compete for government contracts, they do not necessarily support a “rent-seeking” or “corruption” hypothesis. In fact, in testing the “corruption hypothesis” versus an alternative “non-opportunistic motive hypothesis” in the setting of defense contractors’ excessive profits, we find strong evidence refuting the former and in favor of the latter. This suggests that defense contractors may hire those politically connected directors and use their experience to serve a benevolent role to the public. For instance, one legitimate use of the political experience is to keep defense contractors from opportunistic profit-seeking behaviors that could reach or even cross federal government regulatory redlines.

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An Analytical Synopsis of Dr. Ashton Carter's "Should-Cost" Initiatives

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Abstract

Dr. Ashton Carter, Under Secretary of Defense for Acquisition, Technology, and Logistics (USD [AT&L]), and Robert F. Hale, Under Secretary of Defense (Comptroller/Chief Financial Officer), issued a Joint memorandum on April 22, 2011, titled *Joint Memorandum on Saving Related to "Should-Cost."* As iterated in the memorandum, Dr. Carter's goal for the should-cost initiative is to ensure that program managers (PMs) drive productivity improvements into their programs during contract negotiations and throughout program execution and sustainment. This is achievable, according to Dr. Carter, if PMs continuously perform should-cost analysis that scrutinizes every element of government and contractor cost.

In addition to the Joint memorandum, Dr. Carter issued a second memorandum on April 22, 2011, for acquisition and logistics professionals, titled *Implementation of Will-Cost and Should-Cost Management.* This guidance is applicable for all acquisition category (ACAT) I, II, and III programs.

The purpose of this research is to examine the potential impacts this and related directives have on the contracting community's ability to request, acquire, audit, and utilize data germane to contract negotiations and management and whether there may be inherent potential conflicts with the commercial item acquisition provisions of Federal Acquisition Regulation (FAR) Part 12 and the contract pricing initiatives of FAR Part 15 to reduce reliance on the Truth in Negotiations Act (TINA) requirements for certified cost and pricing data and cost accounting standards (CAS), and explore strategies for implementing the directive effectively. Additionally, the research determines the nature and extent of any potential impacts on the Defense Contract Management Agency (DCMA) and Defense Contract Audit Agency (DCAA) at supporting the should-cost effort.

Research Purpose and Objective

In response to skyrocketing program, acquisition, and contract cost on major weapons systems, Dr. Ashton Carter, Under Secretary of Defense (Acquisition, Technology, and Logistics; USD [AT&L]), and Robert F. Hale, Under Secretary of Defense (Comptroller/Chief Financial Officer), issued a Joint memorandum on April 22, 2011, titled *Joint Memorandum on Savings Related to "Should-Cost*." As iterated in the memorandum, Dr. Carter's goal for the should-cost initiative is to ensure that program managers (PMs) drive productivity improvements into their programs during contract negotiations and throughout program execution and sustainment. This is achievable, according to Dr. Carter, if PMs continually perform should-cost analysis that scrutinizes every element of government and contractor cost.

In addition to the Joint memorandum, Dr. Carter issued a second memorandum on April 22, 2011, for acquisition and logistics professionals, titled *Implementation of Will-Cost and Should-Cost Management.* This guidance is applicable for all acquisition category (ACAT) I, II, and III programs.

The objective of this research is to examine the potential impacts this and related directives have on the contracting community's ability to request, acquire, audit, and utilize data germane to contract negotiations and management and to determine whether there may be inherent potential conflicts with commercial item acquisition provisions of FAR Part 12, and Contract Pricing FAR Part 15 initiatives to reduce reliance on the Truth in Negotiations Act (TINA) requirements for certified cost and pricing data and cost accounting standards (CAS), and explore strategies for implementing the directive effectively. Additionally, the research determines the nature and extent of any potential impacts on the Defense Contract Management Agency (DCMA) and Defense Contract Audit Agency (DCAA) at supporting the should-cost effort as iterated.

It is my belief that this work will add value to the current body of work designed to create a culture of efficiency and effectiveness in Department of Defense (DoD) procurement and contracting and provide a highly referenced and readable work useful for policy-makers, practitioners, and academics.

Research Questions

The primary research questions addressed in this paper are as follows:

- What specific impact does Dr. Carter's should-cost directive have on DoD contracting as related to protocols for acquiring commercial items?
- What are the data requirement provisions under protocols for acquiring commercial items versus non-protocols for acquiring commercial items?
- Is the should-cost requirement approach, as defined in the memorandum, achievable under the commercial item acquisition provisions of the Federal Acquisition Reform Act (FARA) and the Federal Acquisition Streamlining Act (FASA), or does the memorandum call for another acquisition strategy using non-protocols for acquiring commercial items?
- If the should-cost memorandum mandates are to be achieved, what specific actions and strategies must be taken by contracting offices to support the mandate?
- Are the DCMA and DCAA able to fully support this initiative, and what specific actions must they take?
- What specific findings and recommendations can be proffered to effectively implement the should-cost initiatives?

Methodology and Scope

This research includes a thorough literature review, examination and assimilation of key policy documents, and outreach to subject-matter experts (SMEs) integral to the should-cost will-cost initiative. Specific sources include, but are not limited to, the following:

- Government Accountability Office (GAO) reports and testimony,
- existing and ongoing research efforts at the Naval Postgraduate School (NPS),
- professional information sources from major systems PM and contracting activities,
- academic literature, and
- SMEs within the DoD and other organizations.

Whenever SMEs are utilized, the DoD and NPS mandate that Institutional Review Board (IRB) protocols be followed to ensure SMEs are given full notification of a researcher's intent to use information gathered from them for research purposes. In accordance with these policies, I obtained consent from all SMEs that I consulted as part of my research for this published work.

Based on the information obtained through this research, I make conclusions and recommendations to professionals desiring a better understanding of the implementation of Dr. Carter's should-cost will-cost initiative, address concerns over potential conflicts with the FARA and FASA, and identify how the DoD may be best structured for achieving the greatest efficiencies and effectiveness at implementation.

Should-Cost and Will-Cost Defined

The definitions of should-cost and will-cost are necessary for an understanding of the concepts and their applicability.

- *Will-cost* is defined as what a program weapons system is likely to cost given a non-advocate (independent) cost estimate, such as in an independent cost estimate (ICE) or independent government estimate (IGE), based primarily on historical cost incurred.
- *Should-cost* is defined as the program weapons system cost adjusted for the program's initiatives or opportunities to reduce cost below the ICE level.

The main difference between will-cost and should-cost is the extensive use of historically incurred cost for will-cost estimates versus the examination of forward-looking efforts at reducing cost in operations.

Better Buying Power: Mandate for Restoring Affordability and Productivity in Defense Spending (June 2010)

On June 28, 2010, Dr. Carter issued the first in a series of memoranda mandating affordability and efficiency in DoD spending. The memorandum for acquisition professionals, titled *Better Buying Power: Mandate for Restoring Affordability and Productivity in Defense Spending* (Carter, 2010a), laid the foundation for all subsequent memoranda issued over the next 15 months. In this memorandum, Dr. Carter called for

> delivering better value to the taxpayer and improving the way the Department does business. … We must abandon inefficient practices accumulated in a period of budget growth and learn to manage defense dollars in a manner that is, to quote Secretary Gates at his May 8, 2010 speech at the Eisenhower Library, "respectful of the American taxpayer at a time of economic and fiscal distress." (Carter, 2010a)

Better Buying Power: Guidance for Obtaining Greater Efficiency and Productivity in Defense Spending and Implementation Directive for Better Buying Power—Restoring Affordability and Productivity in Defense Spending (September 2010)

Dr. Carter subsequently issued two memoranda, again while acting as USD(AT&L); both memoranda were dated and released on September 14, 2010. The first memorandum is titled *Better Buying Power: Guidance for Obtaining Greater Efficiency and Productivity in Defense Spending* (Carter, 2010b) and the second is titled *Implementation Directive for Better Buying Power—Restoring Affordability and Productivity in Defense Spending* (Carter, 2010c).

The memorandum *Implementation Directive for Better Buying Power—Restoring Affordability and Productivity in Defense Spending* (Carter, 2010c) requested the Director,

Defense Procurement and Acquisition Policy (DPAP) to develop the protocols and manpower required to implement the overarching initiatives in the Better Buying Power memorandums. This request included incorporation and integration of key agencies in the protocol and manpower reviews, including the DCMA and the DCAA. An excerpt from this memorandum states,

> Work with the Defense Contract Audit Agency (DCAA) and the Defense Contract Management Agency (DCMA) to develop guidance, which will clearly spell out the roles and responsibilities of each organization in those areas where duplication and overlap occur. Provide recommended guidance to me and to the Under Secretary of Defense (Comptroller) by December 1, 2010.
>
> By October 1, 2010, you are to task DCMA to be responsible for the promulgation of all Forward Pricing Rate Recommendations. In those cases, where DCAA has completed an audit of a particular contractor's rates, DCMA shall adopt the DCAA recommended rates as the Department's position with regards to those. (Carter, 2010c)

Dr. Carter also stated,

> To put it bluntly: we have a continuing responsibility to procure the critical goods and services our forces need in the years ahead, but we will not have ever-increasing budgets to pay for them. We must therefore strive to achieve what economists call productivity growth: in simple terms, to DO MORE WITHOUT MORE. (Carter, 2010c)

Acting on Secretary of Defense Robert Gates' call for obtaining greater efficiencies in DoD procurements, Dr. Carter worked with senior leaders in the acquisition community—including the component acquisition executives (CAEs), senior logisticians and systems command leaders, the Office of the Secretary of Defense (OSD), program executive officers (PEOs), and PMs—to create the Better Buying Power initiatives and guidance. The guidance potentially affected $400 billion of the $700 billion DoD budget spent on goods and services ($200 billion each for weapons, electronics, fuel, etc., and $200 billion for information technology [IT] support). Secretary Gates and Dr. Carter estimated the potential savings from the initiatives and guidance as a significant element of the targeted $100 billion from unproductive to more productive purposes over the five-year period from 2011–2015.

Within the USD(AT&L) guidance memorandum, the should-cost protocol was addressed as a means to reduce unproductive overhead within supporting contractors and to capture reductions in contracts by informing future price and contract-type negotiations (Carter, 2010b). The following is an excerpt from Dr. Carter's September 14, 2010, Better Buying Power memorandum:

> During contract negotiation and program execution, our managers should be driving productivity improvement in their programs. They should be scrutinizing every element of program cost, assessing whether each element can be reduced relative to the year before, challenging learning curves, dissecting overheads and indirect costs, and targeting cost reduction with profit incentive—in short, executing to what the program should cost. The Department's decision makers and Congress use independent cost estimates (ICE)—forecasts of what a program will cost based upon reasonable extrapolations from historical experience—to support budgeting and programming. While ICE Will Cost analysis is valuable and credible, it does

not help the program manager to drive leanness into the program. In fact, just the opposite can occur: the ICE, reflecting business-as-usual management in past programs, becomes a self-fulfilling prophecy. The forecast budget is expected, even required, to be fully obligated and expended.

To interrupt this vicious cycle and give program managers and contracting officers and their industry counterparts a tool to drive productivity improvement into programs, I will require the manager of each major program to conduct a Should Cost analysis justifying each element of program cost and showing how it is improving year by year or meeting other relevant benchmarks for value. Meanwhile, the Department will continue to set the program budget baseline (used also in ADMs and Selected Acquisition Reports (SARs)) using an ICE. We will use this method, for example, to drive cost down in the Joint Strike Fighter (JSF) program, the Department's largest program and the backbone of tactical air power for the U.S. and many other countries in the future. This aircraft's ICE (Will Cost) average unit price grew from $50 million Average Unit Procurement Cost (APUC) when the program began (in 2002 dollars, when the program was baselined) to $92 million in the most recent ICE. Accordingly, the JSF program had a Nunn-McCurdy breach last year and had to be restructured by the Secretary of Defense. As a result of that restructuring, a Should Cost analysis is being done in association with the negotiation of the early lot production contracts. The Department is scrubbing costs with the aim of identifying unneeded cost and rewarding its elimination over time. The result should be a negotiated price substantially lower than the Will Cost ICE to which the Department has forecasted and budgeted. Secretary Gates indicated in his Efficiency Initiative that the Service that achieved the efficiency could retain monies saved in this way; in this case the Air Force, Navy, and Marine Corps could reallocate JSF funds to buy other capabilities.

The Department will obligate about $2 trillion in contracts over the next five years according to Will Cost estimates, so savings of a few percent per year in execution are significant.

The metric of success for Should Cost management leading to annual productivity increases is annual savings of a few percent from all our ongoing contracted activities as they execute to a lower figure than budgeted. Industry can succeed in this environment because we will tie better performance to higher profit, and because affordable programs will not face cancellation. (Carter, 2010b, pp. 3–4)

This excerpt, on close examination, promoted a forward-looking analysis of contractors' embedded practices and associated cost for production as the should-cost position on which PMs must focus, rather than on the initial and/or existing will-cost position that serves as the initial baseline for the program.

Implementation Directive for Better Buying Power—Obtaining Greater Efficiency and Productivity in Defense Spending (November 2010)

Dr. Carter's seven-page November 3, 2010, memorandum, titled *Implementation Directive for Better Buying Power—Obtaining Greater Efficiency and Productivity in Defense Spending*, reiterated guidance provided in prior memoranda and specified actions that the secretaries of the military departments and directors of defense agencies should execute immediately or in the time frame specified within the memorandum. The memorandum also

stated that additional actions in support of the initiatives proffered in the memoranda dated September 14, 2010, would be developed over the following weeks and months. The memorandum addressed five specific areas from the September 14, 2010, memoranda: (1) targeting affordability and controlling cost growth, (2) incentivizing productivity and innovation in industry, (3) promoting real competition, (4) improving tradecraft in service acquisition, and (5) reducing non-productive processes and bureaucracy.

Will-cost and should-cost are specifically addressed in the following excerpt from Dr. Carter's memorandum:

> Effective November 15, 2010, you will establish "Should Cost" targets as management tools for all ACAT I programs as they are considered for major MS decisions. As described in my September 14, 2010, Guidance to the acquisition workforce, "Should Cost" targets will be developed using sound estimating techniques that are based on bottom-up assessments of what programs should cost, if reasonable efficiency and productivity enhancing efforts are undertaken.
>
> These costs will be used as a basis for contract negotiations and contract incentives and to track contractor and program executive officer/project manager performance. Program performance against "Should Cost" estimates will be reported to the Office of Acquisition Resources and Analysis through Acquisition Visibility Service Oriented Architecture (AV SoA).
>
> By January 1, 2011, you will establish "Should Cost" estimates for ACAT II and III programs as they are considered for component MS decisions. You will use "Should Cost"-based management to track performance of ACAT II and III programs. (Carter, 2010d)

Dr. Carter further invoked the should-cost initiative in addressing poor tradecraft in services acquisitions, stating,

> I will issue further detailed guidance for establishing taxonomy of preferred contract types in services acquisition, but starting immediately, you will ensure that services acquisitions under your control are predisposed toward Cost-Plus-Fixed-Fee (CPFF) or Cost-Plus-Incentive Fee (CPIF) arrangements when robust competition or recent competitive pricing history does not exist. This practice will be used to build sufficient cost knowledge of those services within that market segment. You will employ that cost knowledge to inform the "Should Cost" estimates of future price and contract type negotiations. When robust competition already exists, or there is recent competitive pricing history, you will ensure that services acquisitions under your control are predisposed toward Firm-Fixed-Price (FFP) type contract arrangements. FFP should also be used to the maximum extent reasonable when ongoing competition is used in Multiple Award Contract scenarios. (Carter, 2010c)

In the preceding context, Dr. Carter wanted to build a knowledge base of cost within particular service segments where true competition is not driving the prices paid. This can only be accomplished through contract vehicles that allow for detailed submission of cost estimates in discussions and negotiations and for utilization of that data to support future contract negotiations. Hence Dr. Carter's predisposition for cost-plus-fixed-fee (CPFF) and cost-plus-incentive-fee (CPIF) contract arrangements in non-competitive circumstances.

Programs Initially Covered by Ashton Carter's Should-Cost Initiative

The implementation of will-cost and should-cost management initiatives was targeted at five ACAT I–III programs equally allocated in the Army, Navy, and Air Force. The five programs (shown in Table 1) vary in their current maturity and milestone attainments.

Table 1. Should-Cost Management Example (Pilot) Programs

Air Force	Army	Navy
Joint Strike Fighter (F-35)	Joint Air Ground Missile (JAGM)	Joint Strike Fighter (F-35)
Global Hawk Blocks 30 & 40 (GH BLK 30 & 40)	Black Hawk (UH-60M)	Hawkeye (E-2D)
Space Based Infrared System (SBIRS)	Ground Combat Vehicle (GCV)	Presidential Helo (VXX)
Evolved Expendable Launch Vehicle (EELV)	Paladin Product Improvement (PIM)	Littoral Combat Ship (LCS)
Advanced Extremely High Frequency (AEHF) Satellite System	NETT Warrior	Ohio Replacement Program

Note. The information in this table was adapted from Dr. Carter's *Implementation of Will-Cost and Should Cost Management* memorandum, dated April 22, 2011.

Should-Cost Will-Cost Implementation Memoranda Summary

The Services, Navy, Air Force, and Army, have implemented Dr. Carter's should-cost initiative with striking similarities. Table 2 is an examination of the implementation memoranda key elements and provisions.

Table 2. Implementation Memoranda Key Elements and Provisions
(Yoder, 2012)

Key Common Element	Navy Implementation—ASN (RD&A) Memo July 19, 2011	Air Force Implementation—Dept. of the Air Force Memo June 15, 2011	Army Implementation—Dept. of Army Memo June 10, 2011
Identification of Programs	Yes	Yes	Yes
Definition & Use of Will-Cost	Yes. Independent baseline for program budget and funding. External promulgation allowed.	Yes. Independent baseline for program budget and funding. External promulgation allowed.	Yes. Independent baseline for program budget and funding. External promulgation allowed.
Development of Will-Cost Protocols	Yes. CAPE ICE or service cost position. SECNAVINST 5223.3 DON SCP germane. Will-cost is the program of record estimate and the cost analysis requirements	Yes. Non-advocate baseline developed with Air Force AFPD 65-5 and AFI 65-508 for ACAT I and with approval from product or logistics center financial cost estimating	Yes. ICE existing ACAT I and managed ACAT II defined protocols extend to ACAT III programs. Will-cost estimates used for baselines for budgeting,

	description (CARD).	organization (FMC).	programming, and reporting.
Definition & Use of Should-Cost	Yes. PM develops targets using technical and schedule baselines with applied efficiencies, lessons learned, and best practices in productivity and for informed negotiations under FAR 15.407-4 and DFARS 215.407-4. External promulgation NOT allowed.	Yes. PM develops targets via driving leanness at major milestone decisions. NOT used for budgeting, programming, or reporting outside the department.	Yes. PM drives leanness through should-cost management. Incentivizes targets to performance. NOT for budgeting, programming, or reporting outside the department. Creates informed negotiations under FAR 15.407-4 and DFARS 215.407-4.
Development of Should-Cost Targets	PM responsible for targets. Developed in one or more of three ways: 1) will-cost base with discrete, measureable savings. Recommended for all programs with a will-cost estimate. 2) bottom-up estimate without a formal FAR/DFARS should-cost review. 3) bottom-up estimate with a formal FAR/DFARS should-cost review.	PM responsible for targets along with tracking and reporting. AT&L (ACAT 1D and IAMs) and SAF/AQ (or delegated PEO/DAO) approve should-cost estimates at milestones.	PM responsible for identifying savings opportunities and targets. Not applicable to quick reaction capabilities. PM determines discrete and measurable targets while maintaining realistic technical requirements and schedule. MDA approves should-cost targets. Recommended approaches: (1) will-cost base applying discrete measurable items/initiatives. (2) bottom-up approach without a detailed FAR/DFARS should-cost review. (3) bottom-up with a formal FAR/DFARS should-cost review.
Participants in Should-Cost Target	SYSCOM/PM. May seek assistance	PM with cross-functional teams.	PM with assistance from outside

Development	from the Naval Center for Cost Analysis (NCAA), DCMA, and other PM offices.	Can seek assistance from outside: the AFCAA or DCMA.	organizations such as Deputy Assistant Secretary for the Army Cost and Economics (DASA [CE]) and DCMA.
Milestone A	Will-cost estimate (initial or updated) should-cost management target (initial or update)	Will-cost estimate (initial or updated) should-cost management target (initial or update)	Will-cost estimate (initial or updated) should-cost management target (initial or update)
Milestone B	Will-cost update (initial baseline for Nunn-McCurdy metrics) Should-cost (sets internal program execution baseline) Initial to support contract actions (optional)	Will-cost update (initial baseline for Nunn-McCurdy metrics) Should-cost (sets internal program execution baseline) Initial to support contract actions (optional)	Will-cost update (initial baseline for Nunn-McCurdy metrics) Should-cost (sets internal program execution baseline) Initial to support contract actions (optional)
Milestone C	Update will-cost and should-cost. Indirect/direct contract cost reviews (optional) FAR 15.407-4 and DFARS 215.407-4	Update will-cost and should-cost. Indirect/direct contract cost reviews (optional) FAR 15.407-4 and DFARS 215.407-4	Update will-cost and should-cost. Indirect/direct contract cost reviews (optional) FAR 15.407-4 and DFARS 215.407-4
Full-Rate Production Decision/Contract	Update	Update	Update
Withholding and Distribution of Funds	Yes, delta withheld. SAE for ACAT I, MDA for ACAT II, PEO for ACAT III	Yes, delta withheld. Remains in program element. Release by service/component acquisition executive (S/CAE)	Yes, delta managed consistent with the type of contracts used in the program. When fixed-price contracts are utilized, any delta should be considered "realized" and built into the contract.
Reporting Templates	Yes	Yes	Yes

Analysis of the Potential Impacts of Ashton Carter's "Should-Cost" Memorandum on Defense Contracting—Findings and Recommendations

The following summarizes key findings and recommendations presented in NPS-CM-12-199 (Yoder, 2012):

- **Finding & Recommendation #1: FARA and FASA**
  There is a conflict in the specific definition of *commercial item acquisition* that allows for major weapons systems procurements in limited- or non-competitive marketplaces to be characterized as commercial under FARA and FASA statutes. Current legislative proposals are under congressional review to revise the statutory definition.

- **Finding & Recommendation #2: Personnel**
  The DCMA, the DCAA, and the Services have made, and are re-capitalizing their workforce with credentialed personnel in key functional specialties needed to support the should-cost initiative. Key functional specialties include, but are not limited to, auditors and production specialists, with additional specialties in Lean Six Sigma, process management, and so forth. The personnel increases must be protected against any potential cuts to ensure that cost consciousness and reduction in systems acquisition cost can mature and flourish—continue to re-capitalize the workforce.

- **Finding & Recommendation #3: Platforms**
  The CBAR data system has recently been deployed by DCMA. This platform was established in March 2011, providing necessary single-point access to key information spanning DoD-wide contracts and relevant information required for contracting officers to produce pre-negotiation business clearances, sometimes known as business clearance memoranda (BCM), as a pre-cursor to conducting negotiations pursuant to a contract award, and data for the continued management of contracts with real-time actionable information available 24/7 via a secure network. Although the DCMA and DCAA will drive much of the data input, all DoD services and systems commands will have it, and have key roles in populating and managing data in the system. The CBAR system must be funded to maintain accurate and recent data. The data must be relevant and germane to the should-cost effort, which will take quality personnel to define, collect, and populate the data. Continued management and maintenance of this system is imperative and must have high-level support.

- **Finding #4: Protocols**
  Notwithstanding the FARA and FASA findings and recommendations mentioned previously, the protocols for should-cost analysis have been promulgated with an emphasis on flexibility. This flexibility allows program offices the highest degree of latitude in determining should-cost targets and how to achieve those targets. That information must be shared within the government for future target savings and contract negotiations. Continue to emphasize Service program office entrepreneurship at developing individual targets. Share information, internally, with other program and contracting offices via the CBAR.

- **Finding & Recommendation #5: Should-Cost Target Savings Holdback**
  There is concern that if not managed properly, holdback funds may be re-allocated for purposes other than improvements in immediate weapons systems acquisition, thus creating a huge disincentive for program offices to set aggressive should-cost targets. Senior leaders must provide incentives for the program offices to set aggressive should-cost targets, wherein the will-cost versus should-cost potential savings have a guaranteed amount or percentage; I'll call it a cost savings incentive (CSI) that can be used for

program purposes and objectives. The program office can utilize the CSI amount, which perhaps represents either the entire delta or a portion of it.

- **Finding & Recommendation #6: Metrics and Determining Success** Meaningful metrics to determine the efficacy of the should-cost initiative are needed by Milestone authorities, PMs and PCOs, although these metrics have yet to be developed and universally promulgated. Sound metrics for cost reductions, efficiency gains and such, must be developed and implemented to determine the efficacy of the should-cost initiative. At a minimum, an ROI can be developed and utilized, capturing the DoD's total loaded labor cost to conduct the should-cost efforts, including organic and contractor personnel dedicated to the efforts, against actual target savings achieved.

Final Thoughts and Further Reading

An Analysis of the Potential Impacts of Ashton Carter's "Should-Cost" Memorandum on Defense Contracting (NPS-CM-12-199; Yoder, 2012), dated September 17, 2012, is much more comprehensive in its presentation of this topic. The original work, NPS-CM-12-199, contains 77 pages of presentation and analysis, along with an additional 95 pages of supporting appendices, for a total of nearly 175 pages—far more detailed than the information it is possible to present in this synoptic examination.

Those interested in this topic, and those who would like additional details, are encouraged to access NPS-CM-12-199 at the Naval Postgraduate School, Acquisition Research Program website (www.acquisitionresearch.org).

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Finally, I thank my three favorite people—my wife, Nicoline, and daughters, Olivia and Katie—for allowing me to cover the kitchen table with hundreds of pages of notes and drafts and for their belief that the mess would eventually become a published work—perhaps worth reading.

Quantifying Uncertainty for Early Life Cycle Cost Estimates[1]

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on empirical research and the development and application of quantitative techniques to software engineering problems. [dz@sei.cmu.edu]

Abstract

Extensive cost overruns in major defense programs are common, and studies have identified poor cost estimation as a main contributor. Research and experience have identified several factors associated with poor cost estimates. These include

- optimistic expectations about the program scope and technology that can be delivered on schedule and within budget;
- the enormous amount of unknowns and uncertainty that exist when these estimates are made about large-scale, unprecedented systems that take years to develop and deploy; and
- the heavy reliance, of necessity, on expert judgment.

In this paper, we describe a new, integrative approach for pre–Milestone A cost estimation called quantifying uncertainty in early life cycle cost estimation (QUELCE). QUELCE synthesizes scenario building, Bayesian belief network (BBN) modeling, and Monte Carlo simulation into an estimation method that quantifies uncertainties, allows subjective inputs, visually depicts influential relationships among change drivers and outputs, and assists with explicit description and documentation underlying an estimate. We use scenario analysis and dependency structure matrix (DSM) techniques to limit the combinatorial effects of multiple interacting program change drivers to make modeling and analysis more tractable.

Finally, we describe results and insights gained from applying the method retrospectively to a major defense program.

Background

The inaccuracy of cost estimates for developing major Department of Defense (DoD) systems is well documented, and cost overruns have been a common problem that continues to worsen (GAO, 2011, 2012). Because estimates are now prepared much earlier in the acquisition life cycle, well before concrete technical information is available, they are subject to greater uncertainty than they have been in the past (RAND, 2007). Early life cycle cost estimates are often based on a desired capability rather than a concrete solution. Faced with investment decisions based primarily on capability, several problems emerge when creating estimates at this early stage (Roper, 2010):

- *Limited Input Data:* The required system performance, the desired architecture of the solution, and the capability of the vendors are not fully understood.
- *Uncertainties in Analogy-Based Estimates:* Most early estimates are based on analogies to existing products. While many factors may be similar, the execution of the program and the technology used as part of the system or to develop it are often different. For example, software product size depends heavily on the implementation technology, and the technology heavily influences development productivity. Size and productivity are key parameters for cost estimation.
- *Challenges in Expert Judgment:* Wide variation in judgment can exist between experts, and the confidence in the input that they provide is generally not quantified and unknown.

- *Unknown Technology Readiness:* Technology readiness may not be well understood, and is likely to be over- or underestimated.

This paper describes the QUELCE method and experiences to date.

An Improved Method for Early Life Cycle Cost Estimation

The quantifying uncertainty in early life cycle cost estimation (QUELCE) method is an integrative approach for pre–Milestone A cost estimation to address the problems associated with early life cycle cost estimation while at the same time providing benefits not found in current cost estimation methods (Ferguson et al., 2011). The method aims to provide credible program cost estimates as distributions rather than point estimates. QUELCE produces intuitive visual representations of the data that explicitly model influential relationships and interdependencies among the drivers on which the estimates depend. Assumptions and constraints underlying the estimates are well documented, which contributes to better management of cost, schedule, and adjustments to program scope as more is learned and conditions change. Documenting the basis of an estimate facilitates updating the estimate during program execution and helps others make informed judgments about estimation accuracy.

The QUELCE method differs from existing methods because it

- uses available information not normally employed for program cost estimation,
- explicitly models uncertainty on the input side of the cost estimation equation in terms of program change drivers,
- enables calculation (and re-calculation) of the cost impacts caused by changes that may occur during the program life cycle, and
- enhances decision-making through the transparency of the assumptions going into the cost estimate.

Figure 1 shows the flow of information in a typical major defense acquisition program (MDAP) acquisition, with blue boxes added to represent the contributions from the QUELCE method.

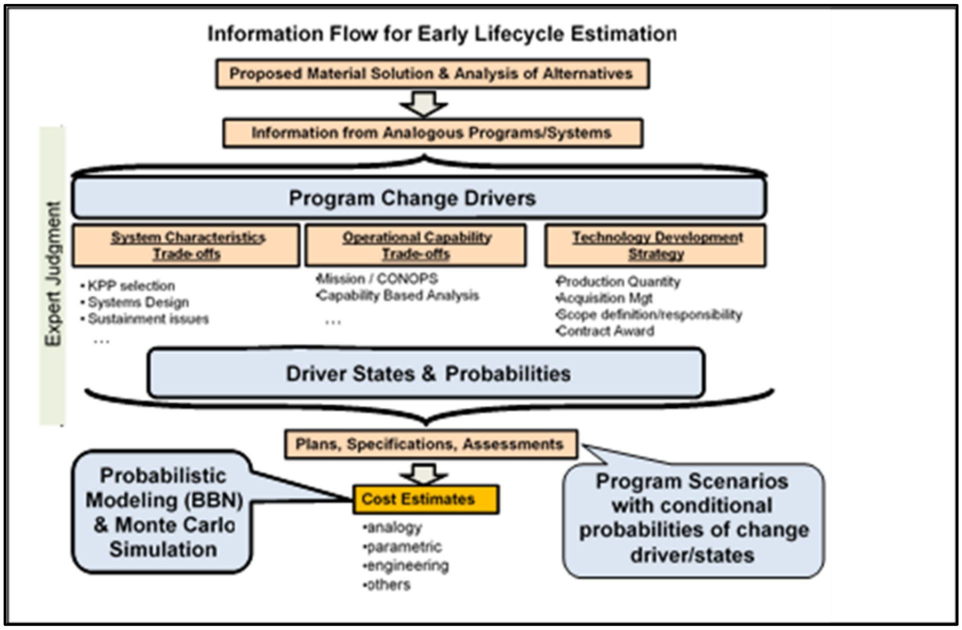

Figure 1. Information Flow for Early Life Cycle Estimation, With QUELCE Method Additions

The QUELCE Method

QUELCE synthesizes scenario building, Bayesian belief network (BBN) modeling, and Monte Carlo simulation into an estimation method that quantifies uncertainties, allows subjective inputs, visually depicts influential relationships among change drivers and outputs, and assists with the explicit description and documentation underlying an estimate. It uses scenario analysis and dependency structure matrix (DSM; Lindemann, n.d.) techniques to eliminate cycling among the interacting program change drivers to make modeling and analysis more tractable. Representing scenarios as BBNs enables sensitivity analysis, exploration of alternatives, and quantification of uncertainty.

The BBNs and Monte Carlo simulation are used to predict variability of what become the inputs to the existing cost estimation models and tools. As a result, interim and final cost estimates are represented as distributions so that the decision-maker can see the probability of a program exceeding the specified cost. The method can be described as a series of five activities, summarized in the following sections.[2]

Identify Program Change Drivers

The identification of program change drivers is best accomplished by the experts who provide programs with information about acquisition, development, and the technical approach, in addition to direct input for cost estimation. A workshop setting is used to identify drivers that could affect program costs. These experts consider all aspects of a program that might change and significantly affect its execution during the program's life cycle—particularly given the new information developed during the Technology Development Phase in preparation for Milestone B. The probability of program success (POPS) factors used by the Navy and Air Force can be used to start the brainstorming and discussion.

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[2] This work was originally described in a two-part series on the SEI blog, A New Approach for Developing Cost Estimates in Software Reliant Systems (http://blog.sei.cmu.edu/post.cfm/improving-the-accuracy-of-early-cost-estimates-for-software-reliant-systems-first-in-a-two-part-series).

In support of this step, we have found that there is much useful information contained in a variety of documents produced during the pre–Milestone A phase. These include the Analysis of Alternatives and the various reports and documents developed as part of the Materiel Solution, the Technology Development Strategy, and, where available, any pre–Milestone A assessments such as the POPS gate reviews. While these traditionally have not been considered for cost estimation purposes, during the conduct of a retrospective study, we found these and other program documents to contain relevant information suggesting several program change factors. Our initial list totaled nearly 60 factors.

In the workshops, experts are asked to provide judgments about the status of each program change driver. The specific, assumed state as proposed by the Materiel Solution and Technology Development Strategy is identified and labeled as the nominal state. Experts then brainstorm about possible changes in the condition of each driver that may occur during the program life cycle. The experts identify possible changes that might occur to the nominal state and use their best judgment for the probability that the nominal state will change.

Identify Interdependencies and Reduce Complexity

Once the changed conditions—referred to as potential driver states—are fully identified, participants subjectively evaluate the cause and effect relationships among the drivers. Expert judgment is applied to rank the causal effects. A matrix is developed that provides the relationship between nominal and dependent states and contains the conditional probability that one will affect the other, but not the impact of the change. This exercise can result in a very large number of program change drivers and states identified for an MDAP.

Using dependency structure matrix (DSM; Lindemann, n.d.) techniques, the highly rated change drivers in the matrix can be reduced to an efficient set that has the most potential impact to program execution and, hence, cost. The DSM technique is a well-established method to reduce complicated dependency structures to a manageable size. Furthermore, the technique helps to eliminate cycles in the matrix by transforming the matrix to an upper-right triangle and makes it directly useful for constructing the BBN. An example of a dependency matrix after DSM transformation created during an SEI workshop is provided in Figure 2.

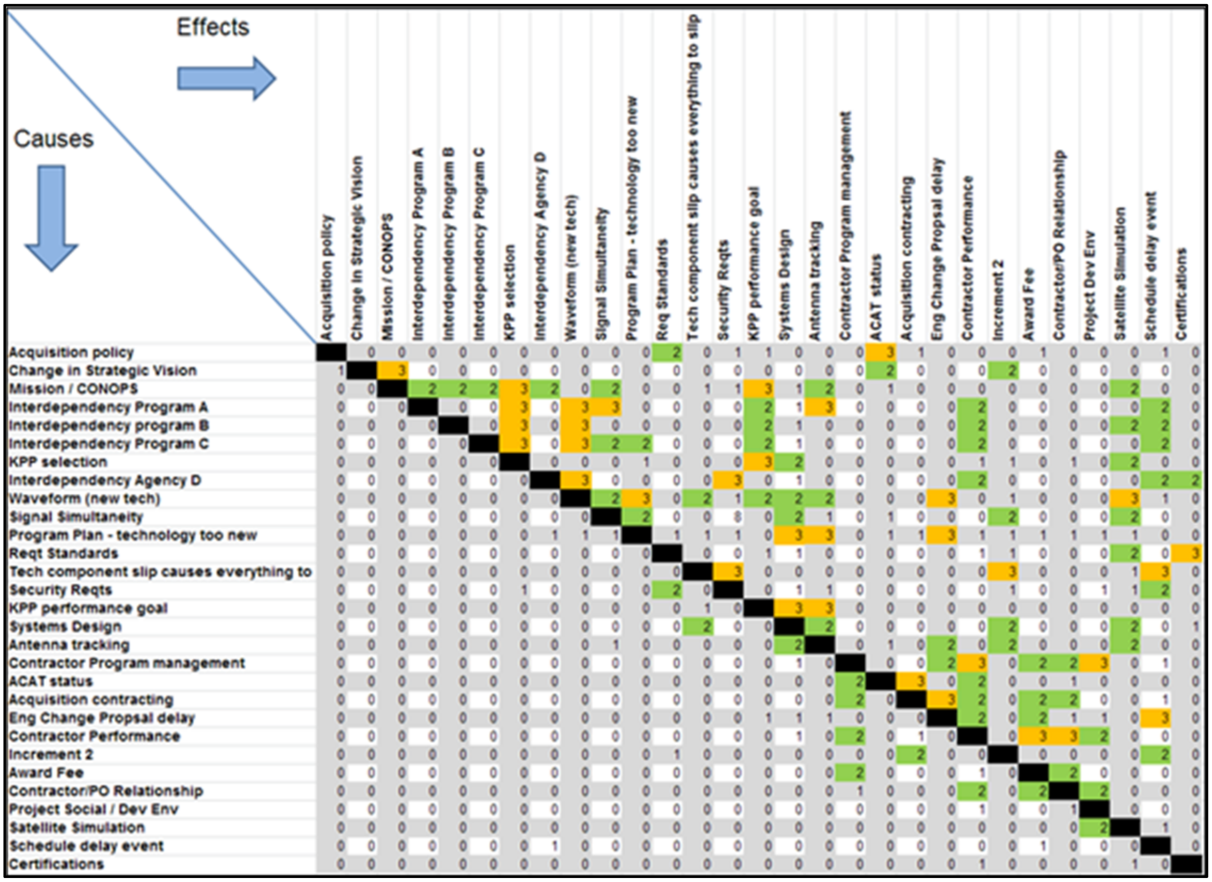

Figure 2. Example Dependency Matrix After DSM Transofrmation

Construct a Bayesian Belief Network

A BBN is constructed using the program change drivers derived from the expert workshop and their cause-and-effect relationships. The BBN models the change drivers as nodes in a quantitative network and includes the conditional probabilities that changes of state in one node will create a change of state in another node, as envisioned by the program domain experts. Figure 3 depicts an abbreviated visualization of a BBN, with circled nodes representing program change drivers and arrows representing either cause-and-effect relationships or leading indicator relationships. This example shows that a change in the Mission & CONOPS driver will likely cause a change to the Capability Analysis driver, which in turn will likely change the Key Performance Parameters (KPPs) driver and subsequently the Technical Challenge outcome factor. The three outcome factors (Product Challenge, Project Challenge, and Size Growth) and their corresponding states are mapped to some of the traditional cost model input factors and their values.

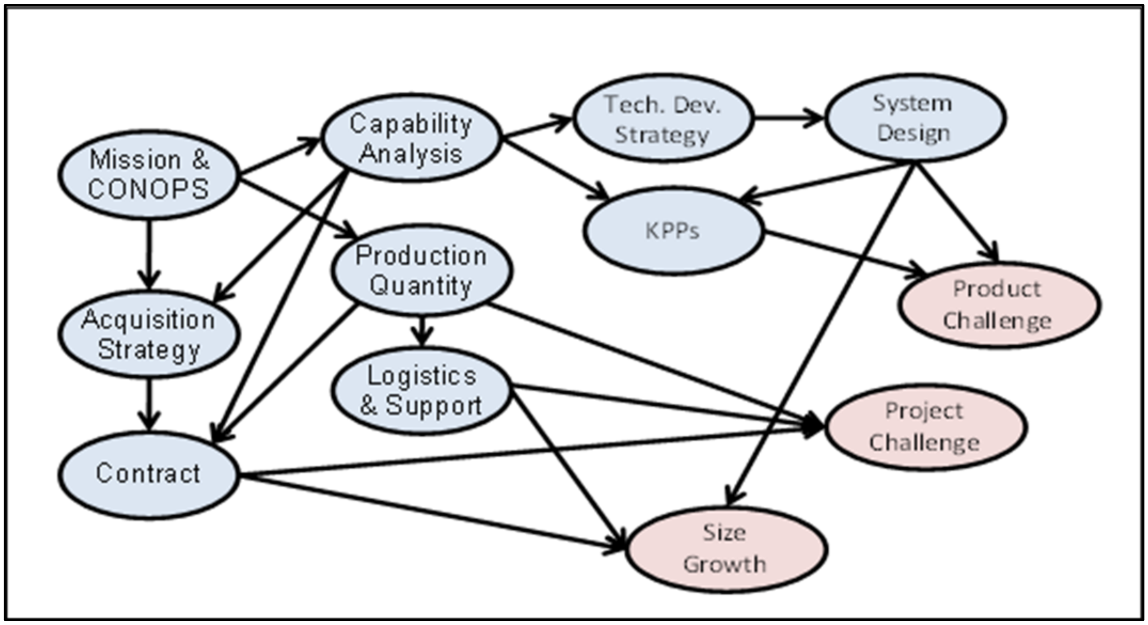

Figure 3. Example BBN

Conditional probabilities are assigned to the nodes (drivers) in the BBN. Each node can assume a variety of states with an associated likelihood identified by the domain experts. This allows the calculation of outcome distributions on the variables.

Domain experts use the BBN to define scenarios. The realization of a potential state in a particular node is specified, and the cascading impacts to other nodes and the resulting change in the outcome variables are recalculated. Any change in one or more nodes (drivers) constitutes a scenario. Once the experts are satisfied that a sufficient number of scenarios are specified, they use their judgment to rank them for likely impacts to cost. An example scenario created during an SEI pilot workshop is provided in Figure 4.

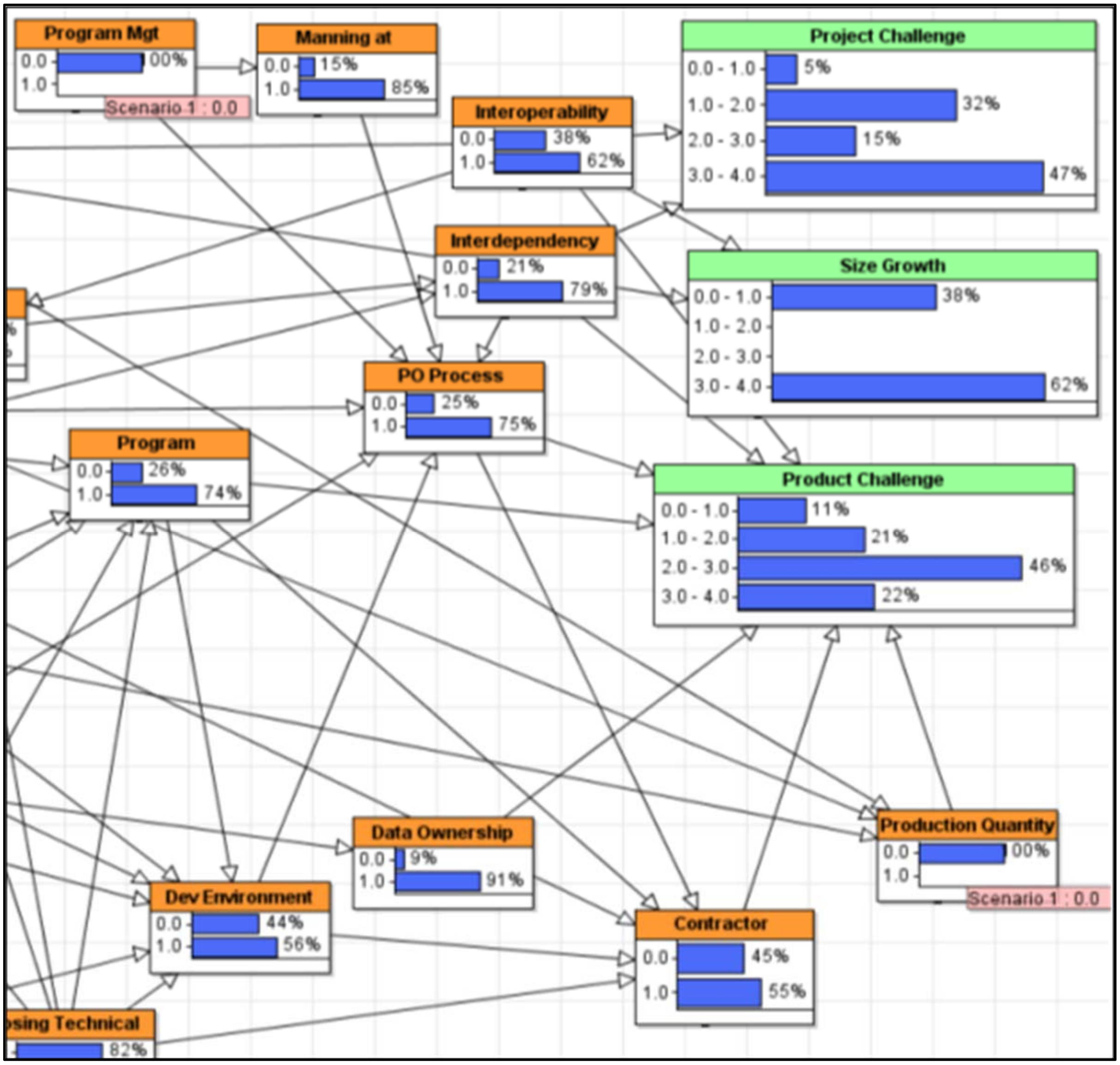

Figure 4. A Partial Example of a Scenario With Two Driver Nodes in a Nominal State

Select Cost Estimating Models to Generate an Estimate

Parametric cost estimation models for software use a mathematical equation to calculate effort and schedule from estimates of size and a number of parameters. A decision is made as to which cost estimating tools, cost estimating relationships (CERs), or other methods will be used to form the cost estimate. COCOMO II is a well-known estimation tool and is open source. The SEI has so far developed the relationships between BBN-modeled program change drivers and COCOMO, shown in Figure 5. The red X's in brackets indicate an inverse relationship between the BBN output factor and the corresponding COCOMO II driver. The black X's indicate a positive relationship. The BBN interface to the commercial SEER-SEM cost estimating tool is currently underway.

Drivers	XL	VL	L	N	H	VH	XH	Product	Project
Scale Factors									
PREC		6.20	4.96	3.72	2.48	1.24	0.00	<X>	
FLEX		5.07	4.05	3.04	2.03	1.01	0.00	<X>	
RESL		7.07	5.65	4.24	2.83	1.41	0.00	<X>	
TEAM		5.48	4.38	3.29	2.19	1.10	0.00		<X>
PMAT		7.80	6.24	4.68	3.12	1.56	0.00		<X>
Effort Multipliers									
RCPX	0.49	0.60	0.83	1.00	1.33	1.91	2.72	X	
RUSE			0.95	1.00	1.07	1.15	1.24	X	
PDIF			0.87	1.00	1.29	1.81	2.61	X	
PERS	2.12	1.62	1.26	1.00	0.83	0.63	0.50	<X>	
PREX	1.59	1.33	1.12	1.00	0.87	0.74	0.62		<X>
FCIL	1.43	1.30	1.10	1.00	0.87	0.73	0.62		<X>
SCED		1.43	1.14	1.00	1.00	1.00			<X>

Figure 5. Mapping BBN Outputs to COCOMO Inputs

The program office estimates of size and other cost model inputs such as productivity are used as the starting point in this step. Often these values are estimated by analogy and aggregation. They are adjusted by applying the distributions calculated by the BBN.

Monte Carlo Simulation

From each selected scenario, we use the output of the BBN to parameterize a Monte Carlo simulation of the inputs to the selected cost estimation model. This provides probability distributions for the input factors to the cost estimating models. This also provides explicit confidence levels for the results. Figure 6 shows the simulation results that the SEI obtained when modeling a factor (person-months) in three different scenarios.

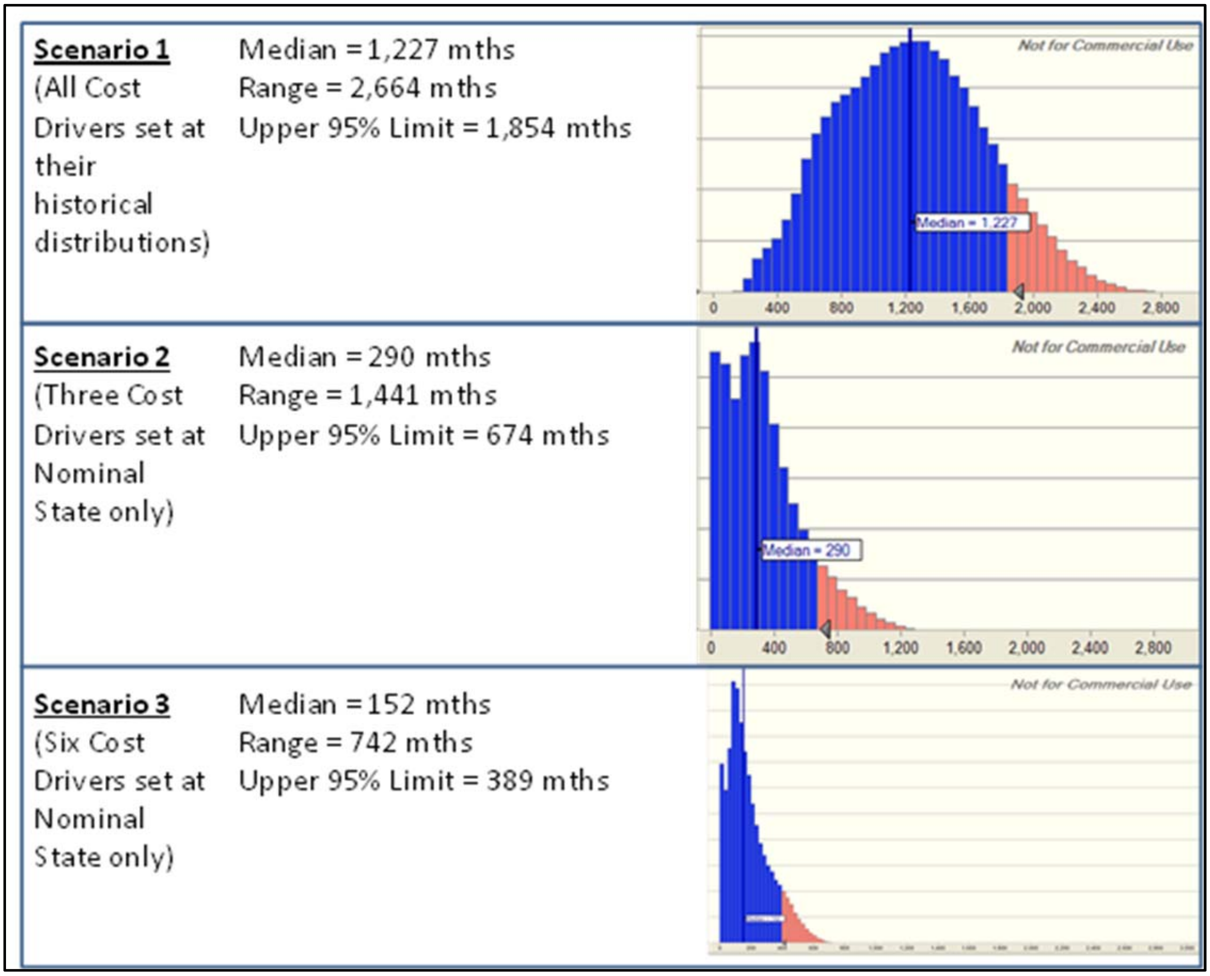

Figure 6. Simulation Results for Three Scenarios

A report with the final cost estimates is generated for each scenario, including the nominal (expected) program plan. The explicit confidence levels and the visibility of all considered program change drivers allow for quick comparisons and future re-calculations. This method enables the creation of comparative scenario calculations at any point during the life cycle. The visibility of the program change drivers and the transparency afforded by the consideration of alternative scenarios—and their assumptions—enables improved decision-making and contingency planning.

Results and Future Research

To date, there have been two empirical thrusts to the research. First, we have conducted a retrospective on an MDAP. We constructed a 10-year time line of the program using archival documents, records from various DoD repositories, and collaborations with SEI staff who worked on the program.

The team accessed over 4,100 program files, which documented virtually all of the program's history. In addition, the team obtained over 100 official contractor submissions of Software Resource Data Reports (SRDRs) and Earned Value Management Reports contained in the Defense Automated Cost Information System. We also obtained acquisition reports from the Defense Acquisition Management Information Retrieval (DAMIR) Purview repository, which included the relevant Selected Acquisition Reports (SARs) and the Defense Acquisition Executive Summary (DAES) Reports.

With the participation of two in-house experts who had worked with the program, we established a provisional set of 57 program-specific change drivers. We also elicited their judgment on the likelihood of change for each of the program change drivers and their potential cascading effect on the other drivers. These judgments formed the basis for implementing DSM techniques to reduce the complexity and capture the cascading effects of the interdependencies among the program change drivers.

DSM reduced the number of program change drivers to those that the experts considered to have moderate or high likelihood of change during program execution. While the matrix manipulation techniques will often remove many of the cycles in the matrix, expert judgment is also required to eliminate cycles that are not removed by the algorithms and rating criteria. In the context of this retrospective, we also realized that asking the experts to mentally reconstruct what potential changes might have been considered at the early stages of the program did not avoid problems in bias based on later experience. But if implemented at pre–Milestone A as envisioned, these judgments represent the reality of the early life cycle estimation process. In the end, we were left with 30 program change drivers that formed the acyclic graph required for the construction of the BBN.

In assigning the required conditional probabilities for the BBN to each change driver, we utilized both the experts' elicited judgments of probability and the ranges of variance produced from the expert calibration experiments performed earlier. The elicited probabilities were used to directly populate some portions of the BBN. However, we quickly realized that it was not feasible to elicit all of the probabilities and conditional probabilities required for such a complex BBN. Hence, we adapted an algorithmic approach to specifying the needed probabilities. To represent the uncertainty in the elicited probabilities and to incorporate this into the computed probabilities, we used the second element noted earlier, the ranges of variance produced by experiments conducted to calibrate expert judgment to a 90% confidence range. This calibration research is the second thrust of this work and is documented in a separate technical report (Goldenson & Stoddard, 2013).

For purposes of demonstration, we relied on using the results of those experiments. However, in a "live action" MDAP, we would use the actual program experts' calibration results, which would be obtained through a calibration test. The technical workshop with the MDAP experts would then serve to both elicit their required judgments as described earlier and allow them to participate in a series of calibration training exercises. The exercises sharpen expert abilities to exert less overconfident and less overoptimistic judgment while also producing the required data for us to capture uncertainty within the BBN.

The resulting retrospective BBN enabled the output of probability distributions used as inputs to the cost estimation tool. We constructed linkages to the SEER-SEM cost estimation tool used by the program for the system software components comprising it. Monte Carlo techniques allowed us to generate confidence intervals for these distributions, which were then used for input to the cost model.

We are close to completing the retrospective and will be comparing the results of the QUELCE model with the estimates and actual costs produced by the program. The conduct of the retrospective helped us refine our elicitation approach, demonstrated the complexity of populating a BBN at scale, and illuminated the need for calibrating teams of experts, not just individuals. Remaining work involves obtaining a review of our decisions about connecting the BBN to cost models such as COCOMO and SEER.

Conclusion

Extensive cost overruns have been endemic in defense programs for many years. A significant part of the problem is that the information used for cost estimates of

unprecedented systems must rely heavily on expert judgments. When done early in the system's life cycle, the estimate is based only on the concept and incorporates much uncertainty as to how that concept will be developed into a fully deployed operational system. QUELCE aims to reduce the adverse effects of that uncertainty. Important program change drivers and the dependencies among them that may not otherwise be considered in forming estimates are made explicit to improve their realism and accuracy. The basis of an estimate is documented explicitly, which facilitates updating the estimate during program execution and helps others to make informed judgments about their accuracy. Variations in the range of possible states of the program change drivers that may occur under different likely scenarios are explicitly considered. The use of probabilistic methods combining Bayesian belief systems and Monte Carlo simulation will ultimately place the cost estimates within a more realistic range of uncertainty.

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Logistics Management

Fully-Burdened Cost of Supply in Self-Sustaining Logistics Networks

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Timothy Reed, *Beyond Optimal Strategic Solutions*

Optimizing Causes of Procurement Cost Through Strategic Sourcing: The Impact of Rate, Process, and Demand

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Fully-Burdened Cost of Supply in Self-Sustaining Logistics Networks

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Abstract

Cost estimates and other analyses for acquisition decisions should incorporate fully-burdened costs of the required commodities in the relevant planning scenarios. In addition to other widely recognized challenges associated with estimating fully-burdened costs of supply, standard approaches systematically produce underestimates for self-sustaining logistics networks. The disparity is especially pronounced when multiple commodities consumed by logistics activities are not locally available. This work develops a model for estimating

resource demands and overall cost associated with self-sustaining logistics networks, which can then be applied to specific examples.

Introduction

Analysis supporting acquisition decisions requires the calculation of fully-burdened costs of resources consumed by the systems being considered. This requires an assessment of planning scenarios under which the systems may be operated. In many cases, an important part of a planning scenario is the logistics network that supports the system. However, a Defense Science Board (DSB) task force was “unable to identify any case where the logistics reductions or deployment and sustainment enhancements achievable from improvements in platform efficiency were quantitatively included as capability improvements and factored into trade-off decisions” (Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics [OUSD(AT&L)], 2008). This work is part of an effort to allow such factors to be included in a quantitative analysis supporting acquisition decisions.

We describe a logistics network as “self-sustaining” if one or more commodities consumed by the logistics activities are not locally available and must therefore be supplied via the network itself. These types of networks are common for operations in undeveloped or disaster-impacted regions. The costs associated with self-sustaining logistics networks are significantly higher than those of traditional logistics networks. Thus, traditional approaches to cost estimation for acquisition decisions tend to underestimate actual costs of operating systems in such environments. It is likely that the implications of the findings of the DSB task force are even more pronounced when the additional factor of self-sustainment is considered. The purpose of this work is to build a framework for estimating fully-burdened cost of supply (FBCS) in self-sustaining logistics networks.

Previous work has identified the existence of a “multiplier effect” for fuel in multi-stage self-sustaining networks. If the warfighter requires X gallons of fuel, some proportion of X is consumed by the preceding stage of the network, and thus some larger amount $X+\Delta$ is required at the start of this stage. The stage preceding that one will in turn consume some proportion of $X+\Delta$, resulting in an even larger requirement. This process continues all the way back to the beginning of the network, where the fuel requirement may be substantially greater than X gallons, depending on characteristics of the network. For more details on the multiplier effect, see Dubbs (2011); Regnier, Simon, and Nussbaum (2012); and Regnier, Simon, Nussbaum, and Whitney (2013).

The multiplier effect is even more pronounced when multiple resources consumed by the logistics activities are not locally available. For example, consider a network in which both fuel and water must be supplied via the network itself. If an additional 1,000 gallons of fuel are needed at the third stage of the network, this may require an extra convoy on the second stage. The extra convoy will not only consume additional fuel, but the additional personnel involved will consume water as well. Thus, the additional fuel requirement increases the requirements for both fuel and water at earlier stages of the network. A notional illustration of this phenomenon is shown in Figure 1. These interactions are not trivial and become larger and more complex if many different commodities must be transported through the logistics network.

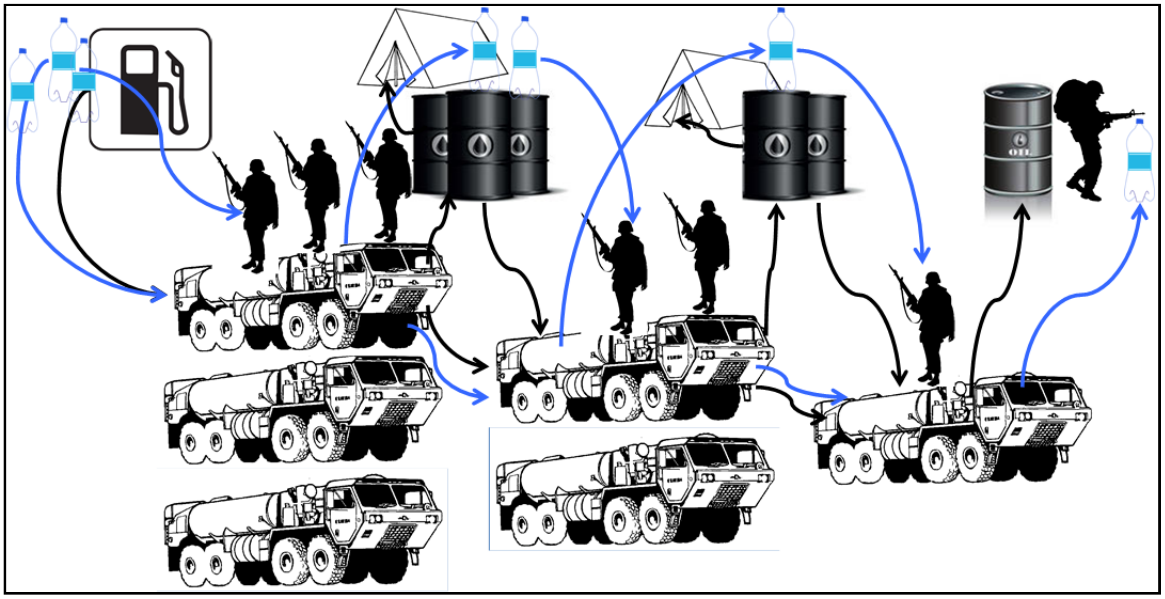

Figure 1. Illustration of the Multiplier Effects and Interactions Between Fuel Demand and Water Demand in a Self-Sustaining Supply Network

Table 1, reproduced from Regnier et al. (2013), illustrates the single-commodity fuel multiplier. In this example, a total of 1,794 gallons of fuel are required at the beginning of Stage 1 in order to transport and deliver 1,000 gallons of fuel to the end of Stage 3. Table 2 shows an example which is similar to that of Table 1, except that it includes two commodities. In this example, a total of 1,000 gallons of supply—fuel and water—are delivered to the end of Stage 3. The fuel requirements of each stage (as a percentage of the supply delivered) are unchanged, and the water requirements (as a percentage of supply delivered) are 90% lower than the fuel requirements. However, transporting either fuel or water requires consumption of both commodities. The total amount of fuel and water required in this example is 1,890 gallons, an increase of 5.4% relative to the Table 1 example, although the per-stage water requirements do not exceed 3%. This demonstrates the impact of multiple commodities on the operating costs of self-sustaining supply networks.

Table 1. Example of a Single-Commodity Self-Sustaining Supply Network
(reproduced from Regnier et al., 2013)

	Fuel Delivered (gal)	Fuel Consumption (% of delivered)	Operating Costs Non-Fuel	Fuel	Total	Total Operating Costs per Gallon Delivered
Stage 1	1560	15%	$3,120	$538	$3,658	$2.35
Stage 2	1200	30%	$2,400	$828	$3,228	$2.69
Stage 3	1000	20%	$2,000	$460	$2,460	$2.46
Total	1794	79%	$7,520	$1,826	$9,346	

Table 2. Example of a Two-Commodity Self-Sustaining Supply Network

	Fuel Delivered (gal)	Fuel Consumption (% of delivered)	Water Delivered (gal)	Water Consumption (% of delivered)	Total Resources Delivered	Operating Costs: Non-Resource	Operating Costs: Resource	Operating Costs: Total	Total Operating Costs per Gallon Delivered
Stage 1	1466	15%	157	1.5%	1,623	$3,732	$616	$4,348	$2.97
Stage 2	1100	30%	120	3%	1,220	$2,806	$926	$3,732	$3.39
Stage 3	900	20%	100	2%	1,000	$2,300	$506	$2,806	$3.12
				Total	1,890	$8,838	$2,048	$10,886	

Note. The model in this example includes consumption of both fuel and water.

As we have noted previously, analyses of costs and requirements should not be conducted independently for each stage, because the resulting quantities are not additive. Similarly, analyses of costs and requirements should not be conducted independently for each commodity, because these resulting quantities are not additive either. Capturing the cross-commodity impacts for many commodities is difficult to do by estimating unit costs of delivery on each stage, especially as the number of commodities supplied via the supply network itself increases.

We have previously used input–output analysis to estimate fully-burdened costs of fuel (FBCF) in single-commodity supply networks, which can be found in the references given earlier in this section. This approach can be extended to include the types of cross-commodity impacts used in the example shown in Table 2. The general input–output approach was developed by Leontief (1970, 1986). Based on the previous application of input–output analysis to FBCF, this work expands the approach to estimate FBCS given any number of commodities in a self-sustaining logistics network.

Model

The multi-commodity FBCS model is presented in this section. Further details and derivations of results were given by Regnier and Simon (2013). The model examines one individual path through the logistics network. Let this path have *n* nodes. We refer to the stage which begins at node *i* and ends at node *i*+1 as stage *i*; the path has *n*-1 stages. We assume there are *m* different commodities transported on it, indexed by *c*. We also assume that all commodities can be expressed in the same units, whether by weight or by volume. The model includes the following parameters:

x_n^c - amount of commodity *c* needed at the destination (exogenously given requirement)

x_i^c - amount of commodity *c* required at node *i*

X_i - total requirement at node *i* . Note $X_i = \sum_{c=1}^{m} x_i^c$

d_i - distance of stage *i* (i.e., from node *i* to node *i*+1)

r_i^c - amount of commodity *c* consumed per unit distance on stage *i*

R_i - total consumption per unit distance on stage *i*. Note $R_i = \sum_{c=1}^{m} r_i^c$

α_i - number of personnel required on convoy in stage *i*

β_i - average speed on stage *i* (includes time spent loading and unloading)

w_i - total convoy capacity on stage *i*, including payload plus internal fuel tanks

a_i^c - amount of commodity *c* consumed at node *i* per hour of labor on stage *i*

A_i - total consumption at node *i* per hour of labor on stage *i*. Note $A_i = \sum_{c=1}^{m} a_i^c$

ϕ_i - operating & support cost per unit of distance for the convoy on stage *i* (i.e., vehicle depreciation, maintenance costs, and any similar costs not explicitly captured in consumption)

y_c - unit cost of purchasing/producing commodity *c* at the start of the supply chain (let y_L represent the cost of labor)

The values of these parameters will, of course, depend on the particular logistics network being analyzed. Many of the parameters are easily obtainable given a familiarity with the network. For example, if the convoy composition for a stage is known, several of the parameters are straightforward to compute.

Analysis

Two intermediate calculations are helpful before presenting any general results. The number of convoy round-trips K_i required on stage *i* can be expressed as

$$K_i \approx \frac{X_{i+1}}{w_i - 2d_i R_i}. \tag{1}$$

The denominator represents the total amount of commodities which can be delivered to node *i*+1 by the convoy on one round-trip. (This expression is an approximation because fractional round-trips are impossible; the size of the error is trivial if the number of round-trips is large.) The model allows for replenishment of logistics assets within a stage—the distance of a stage is not constrained by the internal fuel tank of a transportation asset, for example.

It will also be helpful to compute L_i: the number of labor hours required per convoy round-trip on stage *i*. It can be expressed as

$$L_i = \alpha_i \frac{2d_i}{\beta_i}. \tag{2}$$

Given K_i and L_i, it is possible to compute requirements for each commodity at each node:

$$x_i^c = x_{i+1}^c + \underbrace{2K_i d_i r_i^c}_{\substack{\text{amount of} \\ \text{resource } c \\ \text{consumed} \\ \text{in transport on} \\ \text{stage } i}} + \underbrace{a_i^c L_i K_i}_{\substack{\text{amount of} \\ \text{resource } c \\ \text{consumed to} \\ \text{sustain convoy} \\ \text{personnel} \\ \text{while at node } i}} \tag{3}$$

for $i = 1, \ldots, n-1$. This expression is recursive; the requirements at a given node are a function of the requirements at the following node. Given these relationships between requirements, the total FBCS for this path through the supply network is given by

$$\sum_{c=1}^{m} x_1^c y_c + 2\sum_{i=1}^{n-1} d_i \phi_i K_i + y_L \sum_{i=1}^{n-1} L_i K_i. \tag{4}$$

At the operational planning level, the above calculations are unlikely to be managerially relevant. Many costs included in ϕ_i (e.g., acquisition costs) are sunk. Even variable costs such as labor often cannot be influenced by operational logistics decisions in theater. Labor and other resources may be diverted from other tasks to logistics support, however. More important, at the strategic level, all costs are variable—they may all be influenced by decisions that affect the total end user demand (x_n^c) and efficiency of logistics (a_i^c, r_i^c, and ϕ_i).

The total FBCS estimate is intended to be used in strategic-level assessments of the magnitude of costs of supply to a particular area. However, being able to compute the overall FBCS also allows us to answer more specific questions about the impacts of acquisition decisions on total costs.

To build a framework for answering the types of questions relevant to acquisition decisions, we will introduce several concepts analogous to the fuel multiplier in a single-commodity network. One such concept is a *stage multiplier* Λ_i, which is expressed for any stage *i* as

$$1+\frac{2d_iR_i+L_iA_i}{w_i-2d_iR_i}. \tag{5}$$

The stage multiplier shows the increase in total requirement at node *i* per unit of increase in the total requirement at node *i*+1. Another helpful concept is a *cross-commodity factor* χ_i^c, which is expressed for any commodity *c* and stage *i* as

$$\chi_i^c=\frac{2d_ir_i^c+a_i^cL_i}{w_i-2d_iR_i}. \tag{6}$$

The cross-commodity factor shows the increase in the required amount of commodity *c* at node *i* per unit of increase in the amount of a different commodity required at node *i*+1.

Based on Equations 5 and 6, it is possible to construct a factor which captures such relationships across multiple stages, denoted as χ_{ij}^c. This factor is expressed as

$$\chi_{ij}^c=\sum_{i'=i}^{j-1}\left(\chi_{i'}^c\prod_{j'=i'+1}^{j-1}\Lambda_{j'}\right) \tag{7}$$

for any commodity *c* and nodes *i* and *j*, *i* < *j*. It indicates the increase in the amount of commodity *c* required at node *i* per unit increase in the amount of a different commodity required at node *j*. Note that Equation 7 expresses the relationship between the consumption of a commodity at a given node with the requirement of any other commodity at any other node. In particular, when *i* = 1, Equation 7 shows the additional amount of commodity *c* needed at the beginning of the supply network, which can be used to determine the impact on total cost. Further details and mathematical results were given by Regnier and Simon (2013).

For example, consider a new platform which decreases the warfighter's fuel requirement by Δ gallons. The cost savings resulting from a decrease in the FBCS would be given by

$$\sum_{c=1}^{m} y_c \chi_{1n}^{c} \Delta . \tag{8}$$

These savings are in addition to the savings achieved as a result of not consuming those Δ gallons of fuel themselves, which would be equal to Δ multiplied by the per-gallon market price of fuel at the start of the network.

Discussion and Conclusions

The model given above applies to any mode of transport and can model multi-modal logistics networks—for example, a sea-based stage, followed by ground transportation, followed by air delivery. However, there are some important systematic differences by mode. In Regnier et al. (2013), we provided a model of ground-based transport, in which each stage's resource requirements are determined by the distance and the composition of a logistics convoy. This model is single-commodity but nevertheless highlights the fact that land-based stages are highly sensitive to variations in terrain and infrastructure that are less relevant to air and sea-based stages. Relative to sea-based transport, the assumption of a large number of round-trips is more appropriate. In addition, because the payload of each vehicle is much smaller than the payload of a vessel, convoy composition for land stages is more flexible and can be tailored to specific commodity requirement distribution, which supports treating commodities as interchangeable.

Based on the methods in this work, Hathorn (2013) developed a model for fully burdened costs of supply in a naval supply network under different possible threat scenarios. The complete network is shown in Figure 2, reproduced from Hathorn's paper. The models presented previously can be applied to any individual route through this supply network. In Hathorn's model, force protection is an important consideration; multiplier effects and interactions between commodities are much more significant when force protection vehicles are required in addition to transportation vehicles. In the network being studied, fuel is the commodity that has by far the highest level of consumption—over 95%. However, other commodities such as stores and ordnance are included as well.

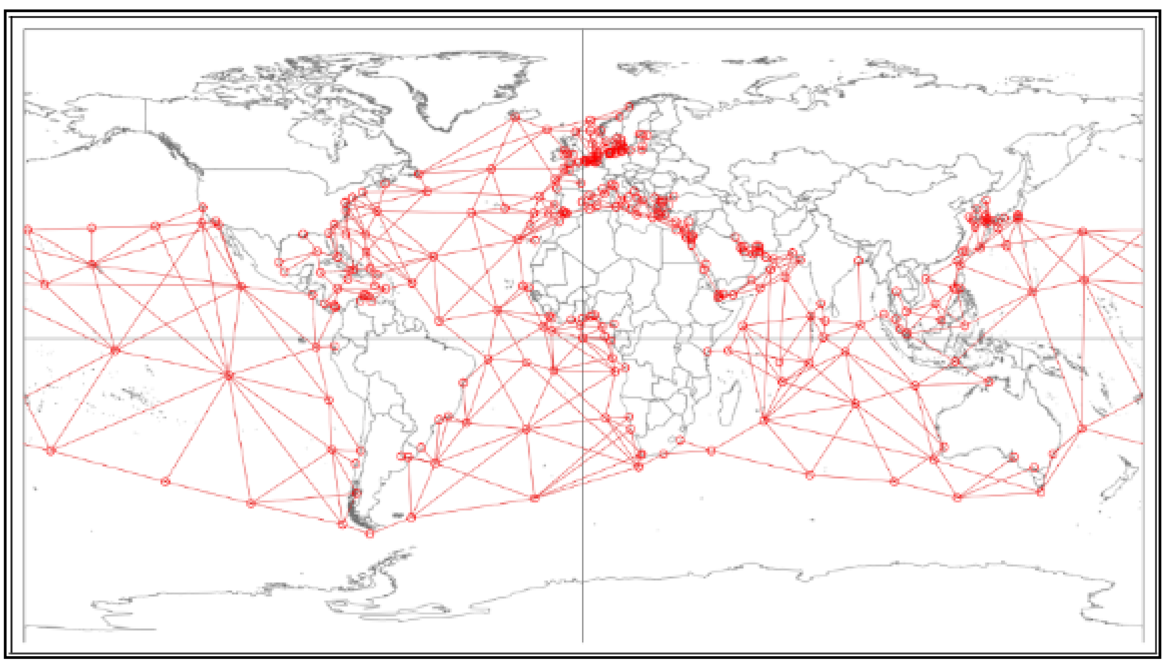

Figure 2. The Nodes and Arcs of a Global Naval Supply Network

(reproduced from Hathorn, 2013)

Hathorn also demonstrated that the FBCS model can be valuable in supporting other types of decision problems. In particular, it allows for route selection decisions to be made with more complete information about costs. Hathorn introduced an optimization model for route selection which determines how to provide a given amount of supply to a specified location at minimum (fully-burdened) cost. Constraints may be added to the optimization model based on the current environment; for example, there may be scenarios in which certain arcs in the network are unavailable.

As an example, Hathorn analyzed a supply route from San Diego to the Spratly Islands. An illustration of this supply route is shown in Figure 3, reproduced from Hathorn (2013). Depending on threat level and convoy composition, the total cost per short ton of supply delivered to the destination ranges from $1,638.70 to $3,144.47. When developing planning scenarios to support decision-making, it is important to consider the possibility of both high-threat and low-threat environments, as the associated fully-burdened costs of supply can be extremely different.

Figure 3. A Possible Supply Route From San Diego to the Spratly Islands
(reproduced from Hathorn, 2013)

Hathorn's work highlights the importance of considering ammunition requirements of the logistics network in a high-threat environment. Consumption of ammunition during force-protection may be considered a requirement—rather than a choice—driven by the threat and thus might reasonably be modeled using planning factors. However, there could be a very wide range of assumptions about the appropriate ammunition consumption rate (parameter r_i^c for *c* = ammunition). In addition, ammunition requires specialized transportation assets, and different kinds of ammunition have very different requirements (cruise missiles vs. anti-submarine torpedoes). Modeling their demand by the warfighter and logistics ammunition requirements in planning scenarios during acquisition is an important but challenging problem.

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Platform Design for Fleet-Level Efficiency: Application for Air Mobility Command (AMC)

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Abstract

The approach presented here combines techniques from multidisciplinary design optimization and operations research to improve energy efficiency-related defense acquisition decisions. The work focuses upon the acquisition of new aircraft for the U.S. Air Force Air Mobility Command missions. Air Mobility Command is the largest consumer of fuel in the Department of Defense, making this a relevant example application. The approach here builds upon previous efforts that examined fleet-level acquisition decisions for commercial airline-related problems, so the paper describes changes necessary to use the problem decomposition strategy of the previous applications in the context of Air Mobility Command. With many of these changes made, the approach is used to simultaneously select requirements for a new cargo aircraft; predict size, weight, and performance of that new aircraft; and also allocate the new aircraft along with existing aircraft. The fuel efficiency of the resulting fleet provides a metric for comparison. The approach, with the abstractions and assumptions used, successfully provides a description of a new cargo aircraft that impacts fleet-level metrics. Results in this study consider a simplistic three-route network and two larger networks, all informed by actual Air Mobility Command data captured by the Global Air Transportation Execution System.

Introduction

The *Energy Efficiency Starts with the Acquisition Process* factsheet (DUSD[AT&L], 2012) states, "Neither current requirements or acquisition processes accurately explore tradeoff opportunities using fuel as an independent variable." The factsheet also states, "Current processes undervalue technologies with the potential to improve energy efficiency." Studies conducted by the Institute for Defense Analyses, the Defense Science Board, Energy Security Task Force, and JASON have all alluded to the significant risk and operational constraints that energy efficiency issues pose on military operational flexibility. The consumption and transport of fuel across a combat theater, throughout the life cycle of operational systems, poses significant operational risk, strategic vulnerability, and increased monetary cost in supporting forward-force assets. Additionally, increasing fuel consumption shifts focus to the acquisition of an increasing number of "tail units" in maintaining forward-force assets. Aviation fuel contributes the largest percentage of energy consumption in the

Department of Defense (DoD), with the Air Mobility Command (AMC) being the single largest consumer (Allardice, 2012). This makes an air mobility-related application relevant for the current research effort.

AMC is a branch of the United States Air Force that is responsible for a wide range of airlift missions that span its global theater of operations. AMC's mission profile mainly consists of worldwide cargo and passenger transport, air refueling, and aeromedical evacuation. AMC also provides transports for humanitarian supplies for major natural disaster around the world. Platforms in operation include C-5 Galaxy, C-17 Globemaster III for long range strategic missions, C-130 Hercules for tactical missions, KC-135 Stratotanker, and KC-10 Extender for aerial refueling missions, and various VIP transport platforms including Air Force One. AMC also utilizes Civil Reserve Air Fleet contractually committed from U.S. airlines (Air Mobility Command*,* 2013).

The complex logistics involved in the transportation of various cargos across its service network requires effective deployment of its fleet of cargo aircraft in meeting daily cargo delivery requirements, while minimizing fuel consumption and subsequent costs. These fuel costs are naturally driven by the choice of aircraft design and individual flight legs flown by the AMC fleet, in meeting cargo obligations within a prescribed schedule timeframe. The identification of cost-saving measures in minimizing fleet-wide fuel consumption is thus intuitively tied into the design of the aircraft itself, and the structure of the routes flown. However, the characteristics of aircraft flown dictate the kind of network that the fleet can serve, thus making it a closely coupled problem.

The objective of this work is to provide a decision-support framework that assists acquisition practitioners in identifying optimal characteristics of new assets (here, aircraft) that can minimize fuel dependency of the entire system architecture in which they serve (here, the fleet of cargo aircraft). This context is driven by the coupled nature that an aircraft design has on fleet operations. The framework in this paper provides a process that can examine how acquisition (and pre-acquisition) decisions describing the requirements for a new aircraft might be made to directly reduce fleet-level fuel usage/cost, considering the operational network and other existing assets along with the potential new (or modified) platform. Consideration of the aircraft design and fleet allocation problems simultaneously presents many decision variables—a condition where the size of the problem rapidly exceeds the mental capability of the designer. Hence, a computational approach becomes necessary to address the complexities associated with the coupled problem. This research will advance the knowledge on how to perform trade-offs with fleet-level fuel consumption as one of the quantities of interest and will enhance understanding about what features this kind of process should entail.

Problem Statement

Previously research at Purdue University has used decomposition strategies that allow a direct connection between the design of a new system (here, an aircraft) and its operations along with other existing systems (here, a fleet of aircraft). The result is an approach that can maximize or minimize a fleet-level objective function by searching for a set of decision variables that describe the new system design and describe the allocation of the new and existing systems to perform operational missions. While a single, monolithic problem statement can reflect this kind of problem, solution of the resulting mixed-integer, non-linear programming problem (MINLP) is difficult, if not impossible. The decomposition strategy breaks down the computational complexity of the decision space into a series of smaller subproblems controlled by a top-level problem. The decomposition approach addresses the issue of tractability, of solving a monolithic, mixed discrete non-linear programming problem, and has yielded better "design solutions" across a set of aviation

applications including commercial airlines, fractional management companies, and air taxi services (Mane & Crossley, 2006, 2012; Mane, Crossley, & Nusawardhana, 2007).The motivation of these prior works in identifying cost- and fuel-saving characteristics of a new, yet-to-be-acquired aircraft bears great similarity to the U.S. Air Force Air Mobility Command (AMC) problem. This paper presents a process that allows investigation of trade-offs between fleet-level fuel usage, performance metrics, and acquisition alternatives for a conceptual problem that resembles missions of the AMC.

AMC's automated air transportation management system, Global Air Transportation Execution System (GATES), is managed by USTRANSCOM and has very detailed information on palletized cargo and personnel transported by the AMC fleet. Cargo transported by the strategic fleet, consisting of C-5 and C-17 aircraft, and the Boeing 747 Freighter (747-F) from the Civil Reserve Air Fleet (CRAF) for long-range missions, are considered as a representative measure of typical cargo flow on the AMC service network. Each data item entered in "GATES Pallet data" represents cargo on a pallet or a pallet-train that was transported. Each pallet data entry item has detailed information about the pallet, such as pallet gross weight, departure date and time, arrival date and time, mission distribution system (MDS), tail number, aerial port of embarkation (APOE), aerial port of debarkation (APOD), pallet volume, pallet configuration, and so forth. These data enable the reconstruction of the route network, pallet demand characteristics, and existing fleet size for our allocation problem.

In this paper, the following assumptions are made on operations of the fleet, based on the available dataset:

In this paper, the following assumptions are made on operations of the fleet, based on the available dataset:

1. The filtered route network from the GATES dataset is representative of all AMC cargo operations.
    a. Demand for the subset served by C-5, C-17, and 747-F (75% of all pallets in the GATES dataset)
    b. Fixed density and dimension of the pallet, representing the 463L pallet type
2. The aircraft fleet consists of only the C-5, C-17, and 747-F. The model is indifferent to variants of these aircraft types.
3. Aircraft operate on a round trip between each base pair to avoid time-of-day scheduling issues and the need for flow balance constraints. A round trip consists of a trip from the hub airport to the outlying base airport and a return trip from the outlying base airport to the hub airport. This assumption played an important role in simplifying the previous work for passenger airline problems and was reasonable for scheduled passenger service. This assumption does not appear as acceptable for AMC cargo operations; however, work to date has not removed this assumption.

Example Baseline Three-Route Problem

We motivate our study with a very simple, illustrative "baseline" problem for AMC operations. In this scenario, a representative route network, consisting of three routes with one shared base, is drawn from the GATES dataset for 2006. A schematic of the sample problem network appears in Figure 1. The three aircraft operated on these routes are the C-5, C-17, and the Boeing 747-F (the latter of which is assumed to be operated as a chartered

aircraft). In this simplified problem, we make the assumption that the aircraft operates on a round trip basis and that the amount of palletized cargo between each base and the Hub base is symmetrical. Route 1 has a range of 2,495 nautical miles with 2,775 pallets transported each way in one year. Route 2 has a range of 325 nautical miles with 2,115 pallets transported. Route 3 has a range of 1,101 nautical miles with 2,199 pallets transported in 2006. The maximum distance of the three chosen routes is 2,495 nautical miles, which allows all three types of current strategic airlift aircraft to provide service on these routes without refueling. The intent is to allocate aircraft to the three routes to satisfy all cargo demand.

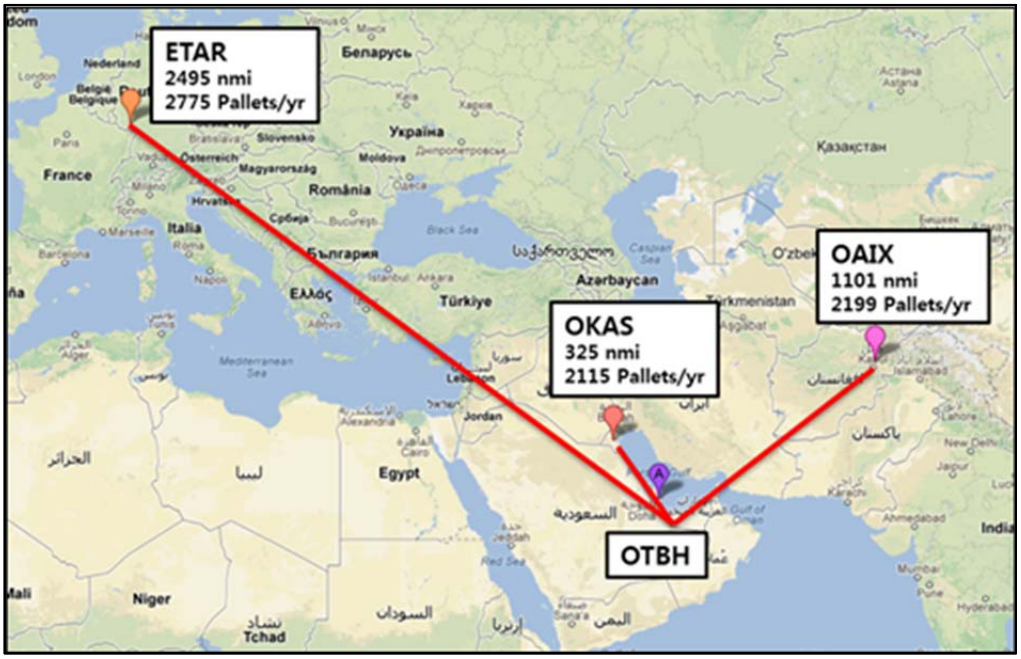

Figure 1. Schematic of Three-Route Allocation Problem

Aircraft Sizing and Costs

When determining which aircraft to allocate to the network routes, the problem formulation will require estimates of the cost, block time, and fuel consumed by each aircraft type in the fleet. A Purdue in-house aircraft sizing code, written in MATLAB, provides these estimates. Jane's Aircraft database (Jackson, Peacock, & Munson, 2004) provided the input parameters for the three existing aircraft types (C-5, C-17, 747-F) used in this study, as shown in Table 1.

Table 1. Existing Aircraft Characteristics

Parameter	C-5	C-17	747-F
Range (nmi)	2,982	2,420	4,445
Pallet Capacity	36	18	29
W/*S* (lb/ft^2)	135.48	161.84	137.34
T/*W*	0.205	0.263	0.286
AR	7.75	7.2	7.7

Direct operating cost (DOC) estimates for commercial aircraft usually include fuel costs, crew costs, maintenance, depreciation, and insurance. DOC estimates are also dependent on the payload, route distance, empty weight, landing weight, and take-off gross weight. While AMC does not have the same operating cost structure, the problem formulation here started using total fleet operating cost as the objective function. Because cost-estimating relationships exist for commercial aircraft, the AMC formulation uses these estimators, even if they may not directly match the costs for AMC operations. The trip DOC of each nominally loaded (based on typical loaded operations) aircraft type, for each route, appears in Table 2.

Table 2. Aircraft Operating Costs of Flight for Each Route

Aircraft Type	Route 1 Cost	Route 2 Cost	Route 3 Cost
Aircraft 1 (C-5)	$130,503	$54,752	$81,671
Aircraft 2 (C-17)	$107,299	$43,858	$66,098
Aircraft 3 (747F)	$141,124	$62,691	$90,358

Figure 2 shows a typical mission profile used for the aircraft sizing and operating missions. To compute the fuel weight necessary for flying the route distance, the fuel required for each mission segment is computed and aggregated. The fuel weight fractions for the different mission segments such as warm-up and take-off, climb, landing and taxi, and reserves are based on empirical data presented in Raymer's textbook (2006). To compute the fuel weight fractions for the cruise and loiter mission segments, the Breguet range and endurance equations are used. The descent segment uses a no-range credit assumption. The reserve fuel fraction is assumed to be 6%, which also accounts for a small amount of trapped and unusable fuel.

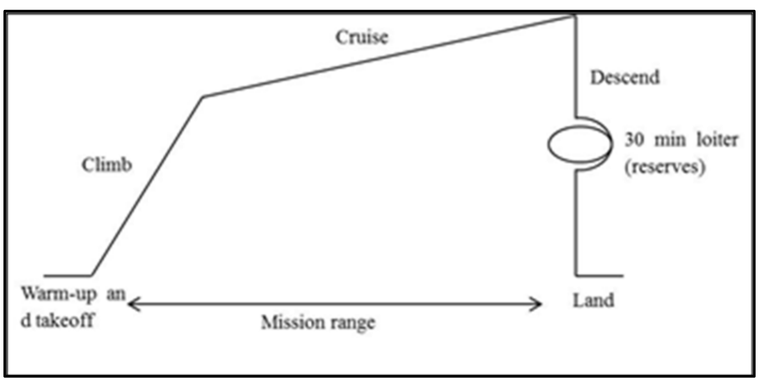

Figure 2. Mission Flight Profile

The payload-range curves for the existing aircraft fleet, depicted in Figure 3, indicate the maximum payload carrying capacity of the aircraft as a function of the distance flown by the aircraft. The payload-range curves for the existing fleet are constructed by using piecewise linear interpolation between specified points from charts presented in Baker, Morton, Rosenthal, and Williams (2002).

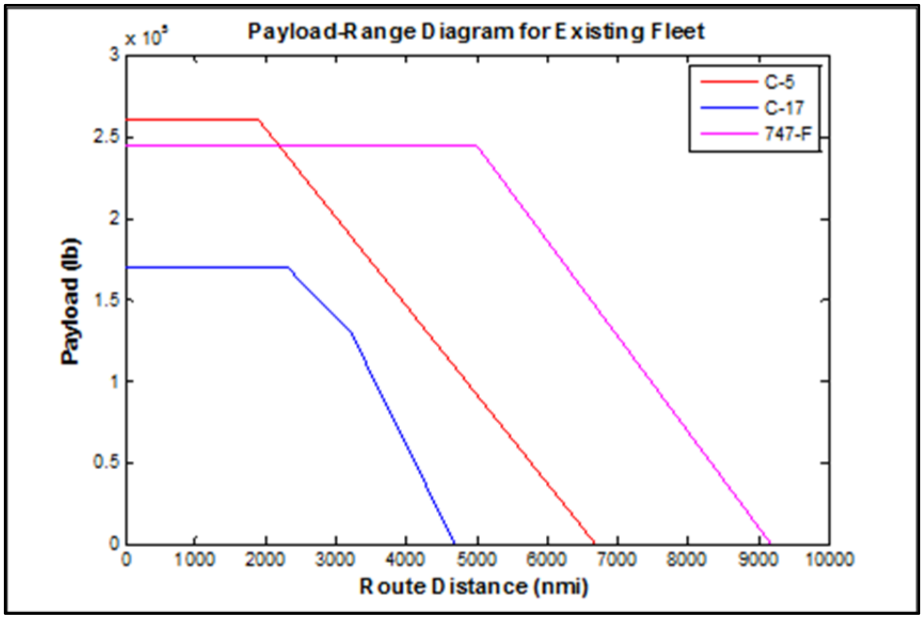

Figure 3. Payload Range Curves for Existing Fleet

Traditional Aircraft Allocation Problem

Using the information provided on the aircraft flight costs (including fuel costs), the objective for the allocation problem seeks to minimize fleet-level DOC by allocating the available fleet to the three routes. Cost coefficients from Table 2 are used in the formulation of the following mathematical programming problem. Mathematical programs have two important aspects of formulation; the *objective function* that reflects the metric being minimized/maximized and *constraints* that reflect resource constraints to the problem. The *decision variables* are the variables of interest that can be manipulated to optimize the objective. The allocation problem statement is as follows:

$$\text{minimize} \qquad \text{Fleet DOC} = \sum_{i=1}^{3} \left\{ \sum_{\substack{A \in C\text{-}5, \\ C\text{-}17, 747\text{-}F}} \left[C_{Ai} x_{Ai} \right] \right\} \tag{1}$$

$$\text{subject to} \qquad \sum_{i=1}^{3} x_{Ai} \le B_{Ai} \quad A = \text{C-5}, \text{C-17}, \text{747-F} \quad \text{(trip limits/aircraft count)} \tag{2}$$

$$\sum_{\substack{A \in C\text{-}5,\ C\text{-}17, \\ B\text{-}747}} Cap_{Ai} x_{Ai} \ge C_i \qquad \text{(capacity)} \tag{3}$$

$$x_{Ai} \in \text{int} \,,\; x_{Ai} \ge 0 \tag{4}$$

In the case of the traditional aircraft allocation problem, the objective function in Equation 1 seeks to minimize the fleet DOC. The decision variable is given by x_{Ai} (with subscripts for aircraft type and route) and is an integer, making the allocation problem an integer programming problem. The total fleet DOC is the sum of costs associated with the number of round trips an aircraft of type *A* flies on route *i*. The constraints expressed in Equations 2 and 3 are the aircraft trip limit and cargo capacity limits on each route (*i*). The trip limit constraints account for the number of aircraft available; the limiting values for

number of trips operated by a given aircraft type in one year are based upon information from the GATES data.

AMC Fleet Allocation Including Design of New Aircraft

Here, we extend the AMC aircraft allocation problem, to consider the potential addition of a new, yet-to-be-designed aircraft, and its impact on fleet-wide operating costs and fuel consumption. The optimization problem now needs to consider the aircraft costs of the new aircraft as a function of the variables describing the new aircraft. The monolithic optimization problem simultaneously considers the aircraft design and allocation of the fleet's aircraft to meet demand obligations and is given by the following equations.

Minimize

$$\text{Fleet DOC} = \sum_{i=1}^{3}\left\{\left[\sum_{\substack{A\in C\text{-}5,\\ C\text{-}17,747\text{-}F}} C_{Ai}x_{Ai}\right] + C_{Xi}\left(Pallet_X,(AR)_X,(W/S)_X,(T/W)_X\right)\right\} \tag{5}$$

Subject to $$\sum_{i=1}^{3} x_{Ai} \le B_{Ai} \quad A = \text{C-5}, \text{C-17}, \text{747-F}, X \quad \text{(trip limits/aircraft count)} \tag{6}$$

$$\sum_{\substack{A\in C\text{-}5,\ C\text{-}17,\\ 747\text{-}F,\ X}} Cap_{Ai}x_{Ai} \ge C_i \quad \text{(capacity)} \tag{7}$$

$$S_{TO}\left(Pallet_X,(AR)_X,(W/S)_X,(T/W)_X\right) \le D \quad \text{(aircraft take-off distance)} \tag{8}$$

$$6 \le Pallet_X \le 36 \tag{9}$$

$$6.0 \le (AR)_X \le 9.5 \tag{10}$$

$$65 \le (W/S)_X \le 161 \tag{11}$$

$$0.18 \le (T/W)_X \le 0.35 \tag{12}$$

$$x_{Ai}, Pallet_X \in \text{int}, \ x_{Ai} \ge 0 \tag{13}$$

Equation 5 is the objective function that seeks to minimize the fleet's DOC. This equation can be modified for different studies as alternate objectives, such as directly minimizing fuel consumption, and so forth, are considered. Equation 6 preserves the aircraft trip limits for a typical year from values calculated from existing flight data; this represents utilization rate. Equation 7 ensures sufficient pallet capacity for cargo traveling on route *i*. Equations 8–13 limit the aircraft design based on minimum take-off distance to ensure that the new aircraft can operate at bases in the network. The continuous design variables describing the new aircraft area were limited to remain near the range of values associated with current cargo aircraft. As in the "traditional allocation" problem, the number of trips of each aircraft type, x_{Ai}, are integers. The coupling of the fleet allocation (integer programming) with the aircraft design (non-linear programming) makes the resource allocation problem a mixed-integer, non-linear (MINLP) problem. MINLP problems are sometimes impossible to solve for even moderate-sized problems. However, we adopt a Multidisciplinary Design Optimization (MDO; inspired subspace decomposition approach from prior literature; Mane et al., 2007) that breaks the monolithic MINLP problem of

Equations 5–13 into a coordinated sequence of more tractable problems, as depicted in Figure 4.

Volumetric load factor is a measure introduced as the ratio of the number of pallets carried to the maximum pallet capacity of the aircraft type. As the density of cargo varies by missions, the average weight of a pallet is calculated from the route data and used as the pallet weight for the entire route. The volumetric load factor of the new aircraft is assumed to be the average of the volumetric load factor of the existing aircraft types on that route.

$$\text{Load factor}_{Xi} = \frac{\sum\limits_{\substack{A = \text{C-5}, \\ \text{C-17}, B-747}} \text{Load factor}_{Ai}}{\#\ \text{of aircraft type operated on route } i} \tag{14}$$

The volumetric load factor formulation, together with average weight of the pallet calculated implicitly, assumes that the new aircraft would be operationally utilized in a similar manner to existing aircraft. The GATES dataset is limited to the AMC operations involving palletized cargo. The design of the new aircraft is strongly influenced by the operational characteristics of the existing AMC fleet and the AMC route network as described in the GATES dataset. However, existing aircraft in the AMC fleet are expected to have the capability to transport outsized cargo and military vehicles in addition to palletized cargo. For instance, the C-5 is capable of carrying two Abrams main battle tanks, an Abrams tank plus two Bradley armored fighting vehicles, 10 LAV light armored vehicles, six Apache attack helicopters, or 36 standard pallets, type 463L (Bolkcom, 2007). The volumetric load factor limitation for the new aircraft based on AMC operations listed in the GATES dataset is a simple and indirect way of ensuring that the new aircraft design meets outsized cargo requirements.

Method and Approach

The consideration of the simultaneous design of a yet-to-be-introduced aircraft and operations of the new aircraft, presents significant computational challenges. We adapt a previously used decomposition strategy, with aviation applications including commercial airlines, fractional management companies, and air taxi services (Mane & Crossley, 2006, 2012; Mane et al., 2007).

Subspace Decomposition Approach

The decomposition strategy, as shown in Figure 4, decomposes the MINLP problem into smaller optimization problems—each sub problem follows the natural boundaries of disciplines involved in formulating the original problem. Prior research (Mane et al., 2007) has applied this decomposition approach to the case of a commercial air transportation problem where the objective is to design a yet-to-be-introduced aircraft that minimizes fleet-level operating cost while meeting passenger demand travel obligations. Here, we adapt the same decomposition approach, adapted to the AMC airlift scenario. The top-level problem, shown in Figure 4, coordinates the aircraft sizing and fleet allocation subproblems.

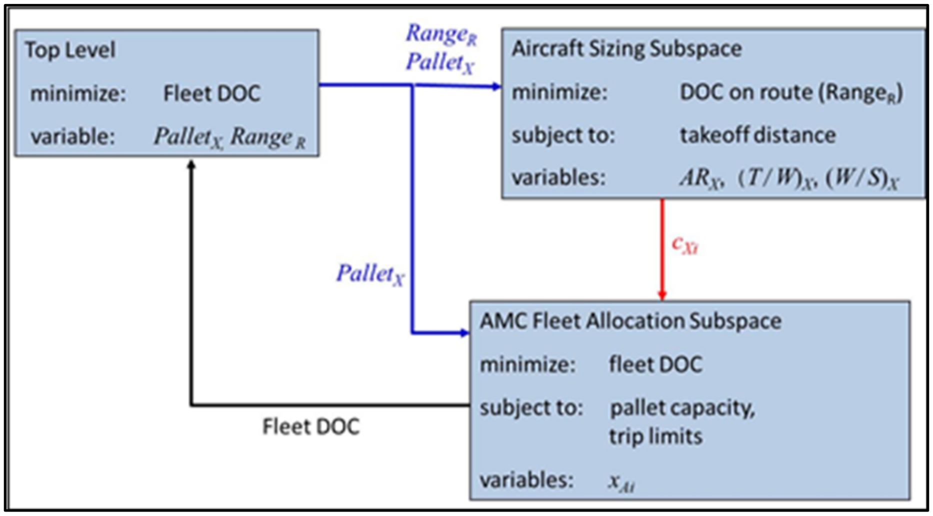

Figure 4. Subspace Decomposition of MINLP Problem

Top-Level Optimization

The top-level problem seeks to minimize the fleet-level DOC using pallet capacity (an integer) and design range (continuous) of the new, yet-to-be-introduced aircraft type *X* as the decision variables; the optimization problem, at this stage, is addressed using a simple enumeration scheme. A quasi-enumeration approach of varying pallet capacity in increments of one and design range in increments of 200 nmi reduces computational time, albeit with the possibility of reduced resolution of the design space. However, the quasi-enumeration approach maps out correct trends for the objective function topology in the solution space. Heuristic algorithms such as Simulated Annealing (SA), Genetic Algorithms (GA), and so forth, may be needed to solve the small MINLP top-level optimization problem for studies involving more computationally intensive and larger sized top-level problem formulations. These top-level decision variables are essentially “design requirements” for the new cargo aircraft design.

Aircraft Sizing Subspace

The pallet capacity and design range of the yet-to-be-introduced aircraft from the top-level problem then become inputs to the aircraft sizing problem. Here, the aircraft sizing problem seeks to minimize the direct operating cost of the new yet-to-be-introduced aircraft, subject to constraints on minimum take-off distance. Operating cost is the aircraft objective here because it matches the top-level objective for minimum fleet cost.

The aircraft design variables are aspect ratio $(AR)_X$, thrust-to-weight ratio $(T/W)_X$, and wing loading $(W/S)_X$. There are many other design variables, but these three have significant impact on the size, weight, and performance of the aircraft. The objective function can be altered to minimize alternative objectives such as fuel burn, and be subject to additional constraints as required. The aircraft sizing problem is a nonlinear programming problem (NLP) and described by Equations 15–20.

$$\text{Minimize} \qquad f = (DOC_{range})_X \tag{15}$$

Subject to

$$S_{TO}\left(Pallet_X, (AR)_X, (W/S)_X, (T/W)_X\right) \le D \quad \text{(aircraft take-off distance)} \tag{16}$$

$$6 \le Pallet_X \le 36 \quad (17)$$

$$6.0 \le (AR)_X \le 9.5 \quad (18)$$

$$65 \le (W/S)_X \le 161 \quad (19)$$

$$0.18 \le (T/W)_X \le 0.35 \quad (20)$$

After finding the aircraft that leads to the lowest operating cost for the aircraft design range, the aircraft performance is predicted for the routes in the cargo network. The allocation subproblem then uses the cost coefficients for the new aircraft, C_{X1}, C_{X2}, C_{X3}, together with the top-level design variables, design range, and pallet capacity, as inputs.

Determination of Number of New Aircraft

The number of new aircraft to be introduced to the existing fleet is unknown *a priori*, because the capacity of the new aircraft is described by the top-level design variable, $Pallet_X$. However, the AMC strategic fleet is expected to be capable of servicing the maximum possible demand scenario by requirement. AMC force structure programmers use the metric million-ton-miles per day (MTM/D) when funding out-year aircraft purchases, and many civilian agencies are accustomed to visualizing fleet capability in terms of MTM/D (Air Mobility Command, 2010). The *Mobility Capabilities and Requirement Study (MCRS) 2016* (Jackson, 2009) illustrates three different scenarios that the capacity of the strategic fleet must always meet. The peak for MCRS Case 1, which represents the highest level of modeled strategic airlift demand, required 32.7 MTM/D. MTM/D values for each type of aircraft are calculated using empirical data. A C-5 carries 0.1209 MTM/D. The newer C-17 carries 0.1245 MTM/D (Kopp, 2004). The Boeing 747-F carries 0.1705, but is not included in calculating strategic airlift fleet MTM/D, because AMC does not operate the Civil Reserve Air Fleet (CRAF). Hence, the 747-F does not affect the number of new aircraft *X* required to meet the peak demand. MTM/D of the new aircraft *X* is calculated using Equation 21. The resulting value is then used to compute the number of new aircraft *X* required.

$$\text{MTM/D} = \frac{\text{Block speed} \times \text{Average payload} \times \text{UTE rate} \times \text{Productivity Factor}}{1{,}000{,}000} \quad (21)$$

The utilization rate (UTE rate) of the new aircraft is assumed to be 12 hr/day, and a productivity factor of 4.8 is assumed for the new aircraft, which is within the typical range of the strategic airlift fleet average value.

AMC Fleet Allocation Subspace

The cost of operating the yet-to-be-introduced aircraft type X on individual routes, C_{Xi}, and with pallet capacity $Pallet_X$ are constants in the aircraft allocation problem. Here, the objective is to minimize the fleet-level direct operating costs using characteristics of the existing and yet-to-be-introduced aircraft (cost coefficients for each route, pallet capacity). Constraints are set such that the number of trips per aircraft does not exceed the trip limit for each aircraft type, and the combined capacity of all aircraft provided meets the demand on each route. The allocation subproblem equations are described by Equations 22–25. As described previously, this approach assumes an aircraft round trip assumption, which removes the need for a node balance constraint; this means the capacity enforced by Equation 24 will be sufficient to carry the largest demand between the two bases connected by route i. The local decision variables in the allocation problem, x_{Ai}—the numbers of trips made by aircraft type A on route i—are integers, making the allocation problem an integer

programming (IP) problem. The Generic Algebraic Modeling System (GAMS) software package, accessed through a MATLAB interface, was used to solve the allocation problem, using the CPLEX solver option (Ferris, 1998.)

$$\text{Minimize} \qquad \text{Fleet DOC} = \sum_{i=1}^{3}\left\{\sum_{\substack{A\in C\text{-5},\\ C\text{-17},747\text{-F},X}}\left[C_{Ai}x_{Ai}\right]\right\} \tag{22}$$

$$\text{Subject to} \quad \sum_{i=1}^{3} x_{Ai} \le B_{Ai} \quad A = \text{C-5},\text{C-17},747\text{-F}, X \text{ (trip limits/aircraft count)} \tag{23}$$

$$\sum_{\substack{A=C-5,\ C-17,\\ B-747,X}} Cap_{Ai}x_{Ai} \ge C_i \qquad \text{(capacity)} \tag{24}$$

$$x_{Ai} \in \text{int}\ ,\ x_{Ai} \ge 0 \tag{25}$$

Solution for Cases

Example Problem Solutions

The MDO decomposition method reduces the computational cost by separating discipline-specific analysis of problems. As described previously, the route network for the three-route example uses data from GATES for demand and to set trip limits. The objective was to minimize fleet DOC for a representative year of operating the fleet. The actual size of the strategic airlift fleet dedicated to cargo transport was obtained from GATES dataset by identification of unique tail numbers, resulting in fleet composition of 92 C-5s, 145 C-17s, and 69 747-Fs. Because this three-route problem is much smaller than the full network reconstructed from the GATES dataset, the number of aircraft and the fleet-level MTM/D value for the three-route problem were reduced proportionally to the pallet demand from the entire GATES dataset pallet demand. The reduced fleet consists of four C-5 aircraft, five C-17 aircraft, and three 747-Fs. Each aircraft type is limited to a trip limit value calculated from the GATES dataset by extracting the number of trips made by each type of aircraft per year. The C-17 has a limit of 53 trips per year per aircraft, the C-17 has a limit of 103 trips per year per aircraft, and the 747-F is limited to 69 trips per year per aircraft. Because the utilization rate of an aircraft depends highly on the aircraft's age, the newly designed aircraft's trip limit is assumed to be 110% of the highest trip limit in the existing fleet, or 113 trips per year per aircraft. These trip limits ensure that the allocation does not exceed the number of available aircraft. Figure 5 shows the results of the partial enumeration employed for the top-level problem, and Table 3 summarizes the solution obtained for the example three-route network.

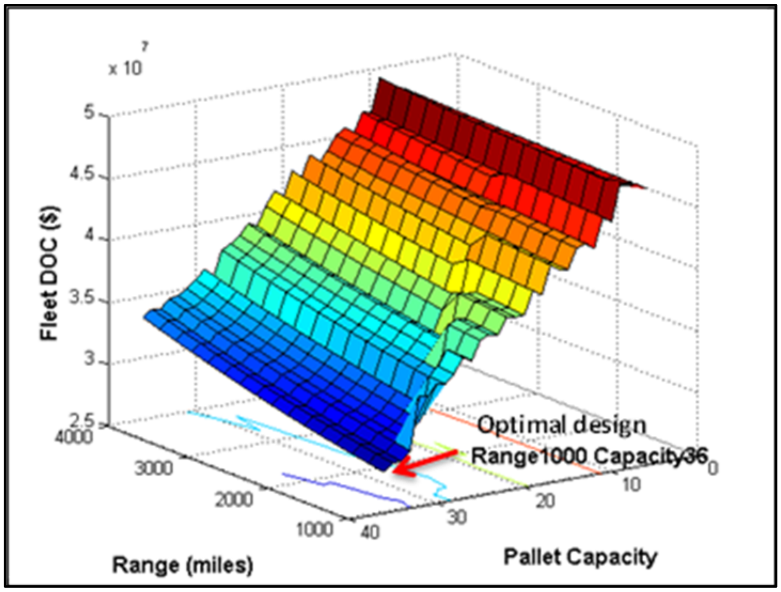

Figure 5. DOC Variation for the Top-Level Design Space for the Three-Route Problem

Table 3. Solution for the Example Problem

Variable, Constraint, Objective	Baseline Allocation	Allocation & Design Solution
$x_{C\text{-}5,1}$ (trips by C-5s on Route 1)	126	0
$x_{C\text{-}5,2}$ (trips by C-5s on Route 2)	0	167
$x_{C\text{-}5,3}$ (trips by C-5s on Route 3)	86	0
$x_{C\text{-}17,1}$ (trips by C-17s on Route 1)	1	0
$x_{C\text{-}17,2}$ (trips by C-17s on Route 2)	236	1
$x_{C\text{-}17,3}$ (trips by C-17s on Route 3)	1	1
$x_{747\text{-}F,1}$ (trips by Boeing 747-F on Route 1)	0	0
$x_{747\text{-}F,2}$ (trips by Boeing 747-F on Route 2)	117	0
$x_{747\text{-}F,3}$ (trips by Boeing 747-F on Route 3)	90	0
x_{X1} (trips by aircraft X on Route 1)	-	133

x_{X2} (trips by aircraft X on Route 2)	-	49
x_{X3} (trips by aircraft X on Route 3)	-	157
Number of new aircraft X introduced	-	3
$Range_{X,}$ nautical miles	-	1,000
$Pallet_X$	-	36
$(W/S)_X$, lb/ft^2	-	104.2
$(T/W)_X$	-	0.208
AR_X	-	6.00
Total pallet capacity on Route 1	4,554	4,788
Total pallet capacity on Route 2	7,641	7,794
Total pallet capacity on Route 3	5,724	5,670
Fleet DOC for one year	$ 49,458,132	$ 28,304,998
DOC saving from baseline	-	42.77 %
Fleet fuel cost for one year	$ 21,716,142	$ 11,597,685
Fuel cost saving from baseline	-	46.59 %

The baseline scenario describes the current fleet operation without the introduction of the new aircraft type X. The results obtained for this allocation problem provide a baseline to measure the effectiveness of introduction of the yet-to-be-designed aircraft in the fleet mix. The allocation problem from the baseline scenario results in a $49,458,132 fleet DOC per year. For these two solutions, the fleet-level fuel consumption is also available. With the newly introduced type X aircraft, the fleet uses almost 47% less fuel. However, this approach clearly customizes the new aircraft to the route network and demand structure. As a result, the new aircraft X is a short-range aircraft with a very large volume; this enables fewer flights of this smaller aircraft to meet demand. Figure 6 emphasizes this result by including the new aircraft's payload-range performance along with the existing aircraft.

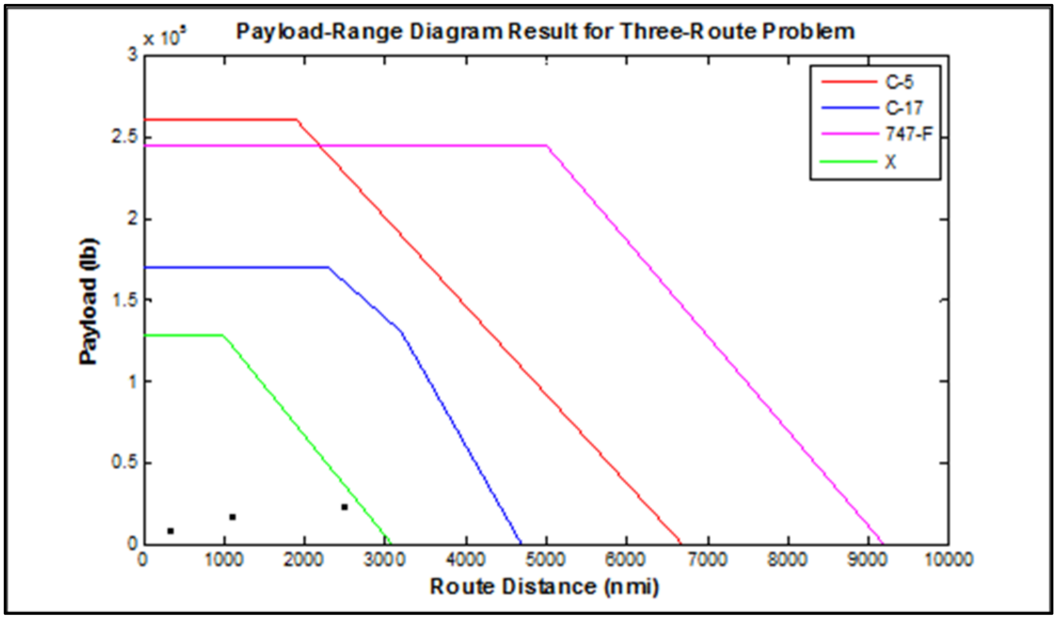

Figure 6. Payload Range Curves for Existing Aircraft and Optimal Aircraft Sizing Solution for Three-Route Problem

AMC Expanded Network Solution

Symmetric Demand Network

The three-route problem provides a simplistic example of AMC operations to illustrate the approach and demonstrate the ability to generate solutions. Increasing the size of the network to investigate the ability to solve larger and more complex network system problems using decomposition is appropriate. Our current formulation assumes a round trip assumption, where each aircraft flies from an origin base to a destination base and then returns to the same origin; this is a reasonable assumption under symmetric demand conditions, which was appropriate for previous commercial passenger airline work. However, many of the routes in the AMC network do not have symmetric demand, because most cargos are transported one way. To study the effects of asymmetric demand and effectively address this issue, we developed a metric that calculates the asymmetry between origin destination pairs (O-D pairs).

$$\text{Demand asymmetry} = \frac{\left|Demand_{O,D} - Demand_{D,O}\right|}{\max(Demand_{O,D}, Demand_{D,O})} \times 100 \quad (26)$$

This approach would be zero if the demand was symmetric. With demand asymmetry calculated on each route, the routes with a demand asymmetry greater than 25% are filtered from the route network before implementing the decomposition approach to simultaneously design the new cargo aircraft while also allocating the fleet to meet demand. Of the 701 routes in the full network reported in GATES, 111 routes have a demand asymmetry of less than 25%. This set of filtered routes represents 16% of total routes and 28% of the pallets, and has an average of 11% demand asymmetry

As the size of the route network and demand increased from the three-route problem, the numbers of aircraft available for use in the problem also increased in proportion to the demand increase. The existing fleet in this symmetric demand problem comprises 27 C-5s, 42 C-17s, and 20 747-Fs. The MTM/D value is also increased in proportion to demand decrease to have more aircraft type X introduced to the fleet. Table 4

summarizes the solution obtained for the symmetric demand route network (although without the per-route detail, given the size of the problem), and Figure 7 presents the partial enumeration scheme to solve the top-level problem.

Table 4. Solution for the Symmetric Demand Problem

Variable, Constraint, Objective	Baseline Allocation	Allocation & Design Solution
$x_{C\text{-}5}$ (trips by C-5)	1,431	1,431
$x_{C\text{-}17}$ (trips by C-17)	3,074	344
$x_{747\text{-}F}$ (trips by 747-F)	1,378	1,380
x_x (trips by aircraft X)	-	1,469
Number of aircraft X introduced	-	13
$Range_{X,}$ nautical miles	-	2,200
$Pallet_X$	-	35
$(W/S)_X$, lb/ft^2	-	113.6
$(T/W)_X$	-	0.227
AR_X	-	6.15
Fleet DOC for one year	$595,393,013	$469,500,435
DOC saving from baseline	-	21.14 %
Fleet fuel cost for one year	$297,067,262	$231,347,251
Fuel cost saving from baseline	-	22.12 %

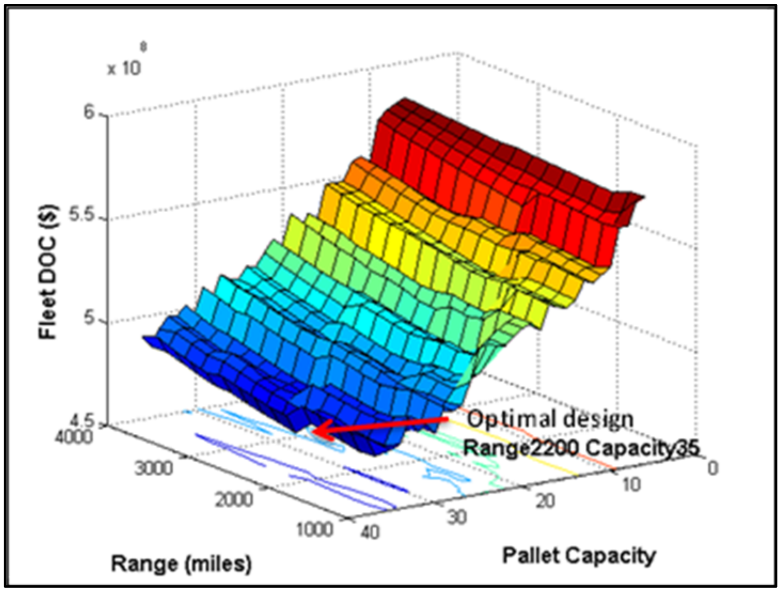

Figure 7. DOC Variation for the Top-Level Design Space for the Symmetric Demand Problem

With the dataset at hand, the allocation of the problem with the introduction of aircraft type X was investigated. The resulting optimal design variable at the top level suggests an aircraft design capacity of 35 pallets and a design range of 2,200 nautical miles. The aircraft sizing subproblem result suggests aircraft type X design with the wing loading of 113.6 lb/ft2, aspect ratio of 6.15, and thrust-to-weight ratio of 0.227. The allocation subproblem introduces 13 aircraft type X in the fleet and provides DOC savings of 21.14% and fuel cost savings of 22.12% compared to the allocation of the fleet without the new aircraft for this symmetric demand scenario. These results also indicate a comparatively short-range aircraft with a high pallet capacity. As apparent from Figure 8, this solution also requires some of the existing aircraft to perform longer range routes, while the fleet cost and fuel savings result by using the newer aircraft on shorter routes.

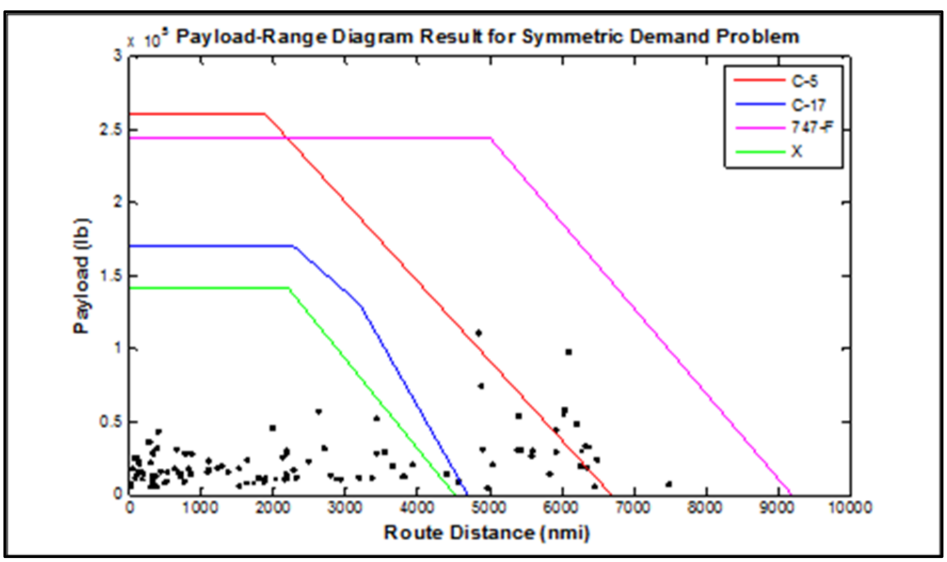

Figure 8. Payload-Range Curves for Existing Aircraft and Optimal Aircraft Sizing Solution for Symmetric Demand Problem

Full Network

Having presented applicability of the decomposition strategy to the symmetric demand problem, the full AMC network problem was attempted. Routes and pallet demand from the entire GATES dataset were considered in this full network problem. The fully considered AMC service network has a 66% demand asymmetry (based on Equation 11).Thus, the round trip assumption may not be reflective of actual operations, but the constraints will ensure there is sufficient capacity in both directions on a route, even if one direction has a substantially lower demand. With this potentially limiting assumption, addressing this problem demonstrates that the approach can scale to larger problems, in terms of routes served. In the full network problem, the round trip assumption implies every trip has symmetric demand resulting in a total of 209,787 pallets delivered between 701 routes. Table 5 summarizes the solution obtained for the full network problem, and Figure 9 illustrates the partial enumeration to find the top-level variables.

Table 5. Solution for the Full Network Problem

Variable, Constraint, Objective	Baseline Allocation	Allocation & Design Solution
$x_{C\text{-}5}$ (trips by C-5)	4,876	4,876
$x_{C\text{-}17}$ (trips by C-17)	6,320	303
$x_{747\text{-}F}$ (trips by 747-F)	4,753	2,112
x_x (trips by aircraft X)	-	5,537
Number of aircraft X introduced	-	49
$Range_{X,}$ nautical miles	-	2,400
$Pallet_X$	-	36
$(W/S)_X$, lb/ft^2	-	114.4
$(T/W)_X$	-	0.228
AR_X	-	6.23
Fleet DOC for one year	$1,743,525,560	$1,370,781,919
DOC saving from baseline	-	21.38 %
Fleet fuel cost for one year	$888,509,686	$693,047,455
Fuel cost saving from baseline	-	22.00 %

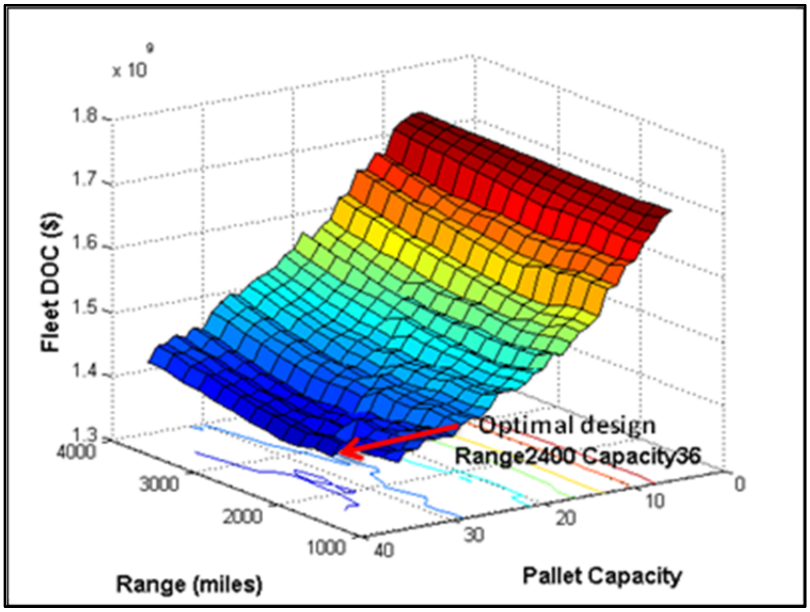

Figure 9. DOC Variation for the Top-Level Design Space for the Full Network Problem

The results suggest the introduction of 49 aircraft type X to the existing fleet with a maximum pallet capacity of 36, using the design pallet weight of 4,003 pounds to set the volume of the fuselage and design range at MTOW of 2,400 nautical miles. The new aircraft again mainly service the shorter routes in the route network as evidenced in Figure 10. The wing loading of aircraft X is 114.4 lb/ft^2, the aspect ratio is 6.23, and the thrust-to-weight ratio of aircraft X is 0.228, which is a slight increase compared to the solution from the symmetric demand scenario due to a slight increase in fuselage size and design range.

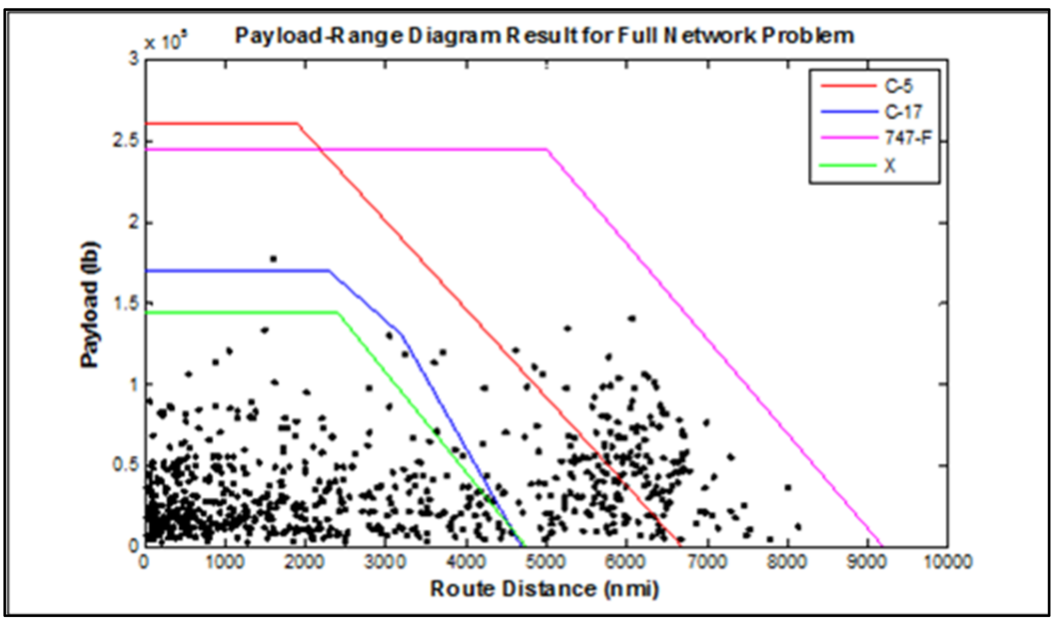

Figure 10. Payload Range Curves for Existing Aircraft and Optimal Aircraft Sizing Solution for Full Network Problem

Future Work and Conclusions

The studies presented here assume simplified demand scenarios to demonstrate the viability and applicability of the decomposition approach in solving problems that represent AMC operations, and as a tool to better inform acquisition decisions. AMC operations typically involve highly uncertain cargo demand operations—a contrasting difference to airline problems that are fairly constant. The uncertainties in cargo demands and shipping priorities manifest as uncertainties in the load factor and quantity of cargo flow between O-D pairs.

The uncertainties in load factor and total cargo can be modeled using a Monte Carlo sampling technique. This model addresses the uncertainty in both demand and load factor, within a probabilistic framework. Through addressing uncertainty via a Monte Carlo sampling technique, the subspace decomposition method can determine a yet-to-be-introduced aircraft design that is tailored to minimize fleet-level cost (fuel/direct operating) under prescribed uncertainty. Future work will reflect a more representative mixture of the AMC fleet from the GATES dataset with uncertainty in the operational characteristics of the fleet and route network.

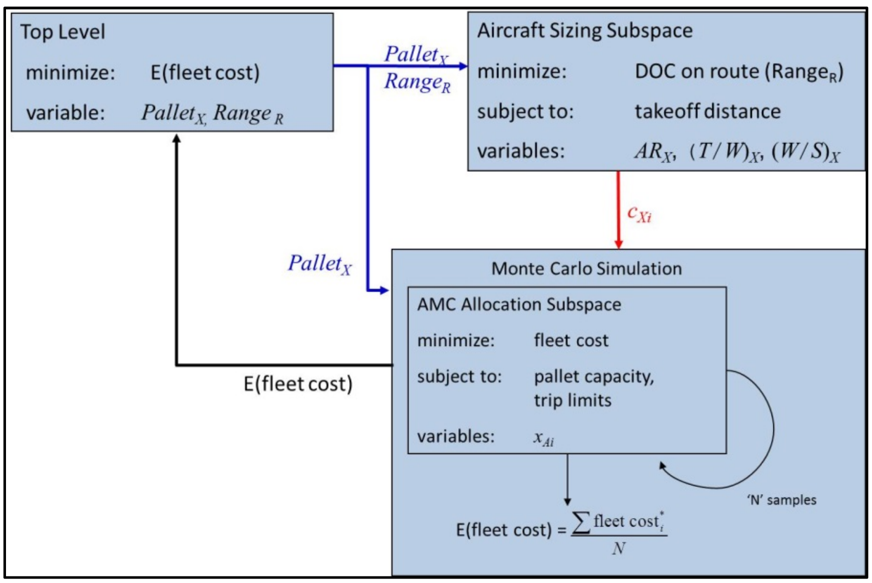

Figure 11. Subspace Decomposition of MINLP Problem With Uncertainty

The round trip assumption, although valid for studies with a symmetric demand route network, appears to be a weak abstraction for the entire network, as mentioned earlier. Future work will consider "scheduling-like" formulations for the resource allocation problem by implementing node balance constraints. The addition of node balance constraints would increase the computational complexity and possibly the computational burden, as individual aircraft tail numbers need to be tracked in the model. However, this formulation allows modeling of varying directional pallet demand between origin destination pairs. An acquisition support issue is the selection of the top-level design variables that represent some of the requirements for a new platform. Payload capacity, design cruise velocity, and range are common aircraft design variables and are logical choices for these top- or system-level variables. Future investigations will consider other platform requirement variables as necessary. The resulting values for these requirement variables can inform acquisition decisions about what new platform requirements will lead to a more successful fleet.

The studies presented here also use direct operating cost as the objective function. This follows from the previous work for commercial airline-related investigations, but here this allows for the chartered 747-F aircraft to be modeled as part of the problem. If a formulation sought to minimize fuel consumed by AMC, it is possible that one solution would lead to carrying all cargo on the chartered 747-F aircraft. As demonstrated previously, fleet-level fuel values are readily available and minimizing DOC has a strong relationship to minimizing fuel consumption.

From the results, all of the newly designed aircraft should be smaller aircraft than the existing aircraft in the strategic fleet. This diversifies the size of the aircraft, and tries to exploit the fact that existing large-size aircraft generally carry only a small fraction of their maximum weight (and in some cases volume) capacity. The smaller aircraft will be used predominantly on routes that are short and will carry a comparatively large number of pallets per flight. In comparison, the scenario in which the new aircraft design and allocation relaxes the load factor imposed on weight suggests an even smaller aircraft that is designed to carry only a small number of palletized cargos weighing approximately 4,000 lbs each. Results suggest that this platform will be even more efficient as many of the routes are short and day-to-day base cargo. The fuel saving in all cases are directly related to the DOC saving as fuel cost is a driving factor in DOC.

The research presented in this paper demonstrates an approach to concurrently design a yet-to-be-introduced aircraft and its fleet-level operations in the context of military airlift operations. The decomposition approach presented in this paper makes the resulting MINLP problem tractable. The solution space of the top-level optimization problem provides a landscape that could help acquisition practitioners make informed acquisition decisions and design choices about the new platform. The design combination of the top-level problem corresponds to different levels of fleet-level direct operating costs, and consequently, different operations (allocation of fleet over service network.)

Although the studies presented here focus on the concurrent design of aircraft to improve fleet-level operational performance metrics, the problem formulation and solution methodology have features that can be extended to other systems of interest and/or the design of multiple yet-to-be-designed systems.

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Improving DoD Energy Efficiency: Combining MMOWGLI Social-Media Brainstorming With Lexical Link Analysis (LLA) to Stengthen the Defense Acquisiton Process

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Abstract

DoD energy inefficiency is a significant liability and a constraint on operations and a force-protection challenge. It is therefore imperative to reduce energy demand and provide operational forces greater flexibility among alternative energy sources. However, the current acquisition processes undervalue technologies with the potential to improve energy efficiency. We report the results of leveraging an innovative platform, the Massive Multiplayer Online Wargame Leveraging the Internet (MMOWGLI) to link and elicit collective intelligence from the acquisition community for the challenge of DoD energy inefficiency. We first linked the existing MMOWGLI energy data with samples of acquisition data using lexical link analysis (LLA). We generated *match matrices* based on themes discovered in both data sets. The themes and match matrices helped identify the gaps and opportunities to apply collective intelligence from the MMOWGLI game to the current acquisition process. This effort demonstrates superb potential of an innovative methodology that can be deployed quickly to mobilize the intellectual capacities of the acquisition community. It may also increase the overall awareness of ongoing acquisition research to warfighters and create a positive impact for the future acquisition decisions to help achieve improved DoD energy efficiency.

Background, Needs, and Research Questions

Studies evaluating the DoD's energy use have been conducted by the Institute for Defense Analyses, the Defense Science Board Energy Security Task Force, and JASON

(an independent scientific advisory group). All three studies suggest that DoD energy inefficiency is a significant liability, a constraint on operations, and a force-protection challenge. More specifically, all three studies led to two consistent requirements for DoD energy efficiency: (1) By reducing energy demand, we may provide operational forces greater flexibility and reduce their dependency on logistics infrastructure; and (2) We can improve the DoD's current requirements and acquisition processes to value the technologies with the potential to improve energy efficiency (DoD Acquisition and Technology, 2012).

The Massive Multiplayer Online Wargame Leveraging the Internet (MMOWGLI), sponsored by the Office of Naval Research (ONR), is an online game platform designed to elicit collective intelligence from an engaged pool of world-wide players. The Naval Postgraduate School (NPS) is one of the primary developers of the game software. Recently, the Navy's Energy and Environmental Readiness Division (OPNAV N45), hosted by NPS Modeling Virtual Environments and Simulation (MOVES) Institute, conducted a civic and military collaboration specifically for examining Navy energy efficiency May 22–25. In the past, the NPS hosted a series of successful games, *piracyMMOWGLI* (2011–present, ongoing) and *energyMMOWGLI* (May 2012), which built the critical mass of players needed to find creative solutions to the real-life difficult problems, such as piracy and energy.

In the energyMMOWGLI game, ideas were collected through "play an idea card" and "take action," as shown in Figure 1. The motivating "call to action" for players is to improve the U.S. Navy's combat capability and energy security, particularly by promoting energy efficiency, reducing energy consumption, and diversifying its energy supply (use of alternative energy) for the sake of future strategic readiness. The overall goal is to reduce reliance on fossil fuels from overseas.

Figure 1. The energyMMOWGLI Game

In this energyMMOWGLI game, 560 players contributed over 5000 ideas and 68 action plans. Lexical link analysis (LLA; Zhao, Gallup, & MacKinnon, 2010, 2011a, 2011b, 2011c, 2012) was used in analyzing the collected data. All results are published online (see MMOWGLI Energy Game, 2012; MMOWGLI Energy Game Portal, 2012; MMOWGLI Business Initiative [BII] Game, 2013; MMOWGLI BII Game Portal, 2013).

- https://portal.mmowgli.nps.edu
- https://portal.mmowgli.nps.edu/energy-welcome
- http://web.mmowgli.nps.edu/energy/IdeaCardChainEnergy2012.html
- http://web.mmowgli.nps.edu/energy/ActionPlanListEnergy2012.html

We leveraged the energyMMOWGLI game in the acquisition community through the following four-step process. Further details appear later in this paper and in the online game portal.

1. Prepare acquisition data. Collate key terms and goal statements of current acquisition programs within the congressional budget processes for use by the LLA methodology.
2. Perform link analysis and correlation. Compare the already-collected energyMMOWGLI results to determine action plan relevance on a program-by-program basis.
3. Design new capabilities for information collection. Define questions for a continuation round of the energyMMOWGLI game, to support programmatic life-cycle needs of the acquisition community.
4. Plan/conduct follow-on games. Conduct a follow-on game focused on shared needs of many energy programs, demonstrating the value of this approach in a formal, repeatable way.

Methodology

MMOWGLI Game

The game is built using a unique, open source, software adaptation of the Institute for the Future (IFTF)—designed game to simulate a real world "brainstorm." A player needs to register with a required game identification (ID) and e-mail. First and last name and other personal identification information (PII) are not required.

The game starts with the explanation of the situation and allows a player to "play an idea" or "take action." Users can then choose to input an idea or participate in the discussion of an existing idea in the categories of "Innovate" and "Defend." The discussion can be in one of the following categories: expand—build on this idea to amply the impact; counter—challenge this idea; adapt—take this idea in a different direction; explore—something missing?; or ask a question, as shown in Figure 2.

In the end, the system will gather collective intelligence that resides in color-coded, tree-structured sets of ideas and discussions in text format as shown in Figure 3. If an idea and its associated discussion have merit, which is determined in the combination of the player's score and the Game Master's recommendation, it will be taken into a separate "take action" board for further planning and deliberation.

Figure 2. Categories of Ideas Based on the Styles of Responses

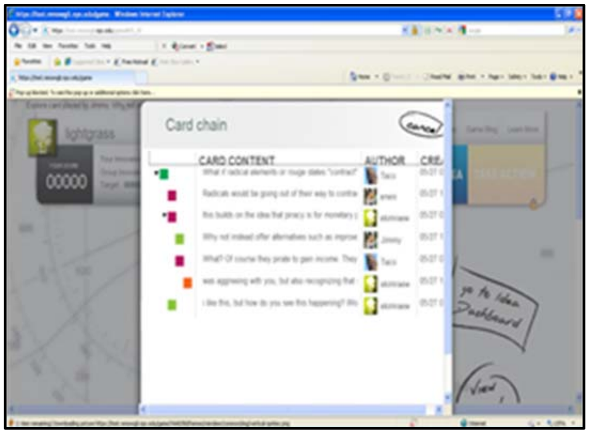

Figure 3. Ideas Collected in the Color-Coded Tree-Structured Categories

The MMOWGLI platform is suitable for tackling a broad range of challenges for national security, multiple stakeholders, and challenges for small or big communities (e.g., corporations and research communities like the acquisition system community). It is a configurable innovation platform that can be adapted to any scenario. For example, an aerospace and defense company, Raytheon, is considering the game engine for use within a company as a corporate innovation platform.

Lexical Link Analysis

LLA is a form of text mining in which word meanings represented in lexical terms (e.g., word pairs) can be represented as if they are in a community of a word network (Zhao et al., 2010, 2011a, 2011b, 2011c, 2012). LLA "discovers" and displays these networks of word pairs from large-scale unstructured data. It can be installed as a search and knowledge management tool for scoring and ranking interesting information and for visualizing and reporting correlations among categories and layers of information including lexical, semantic, and social links. This effort then presents the decision-maker with previously unavailable and emerging patterns and themes, as well as unprecedented levels of analysis, thus reducing the workload and overcoming the blind spots of human analysts and with potential automation. For example, for the recent MMOWGLI games used to develop and identify new ideas about stated subject matters, LLA was leveraged to identify potentially interesting information from "idea cards," link them, then recommend them to the matched action plans for Game Masters.

Figure 4 shows the game's content and attributes, which were processed into the inputs (i.e., meta_data.txt and a directory of text files with idea card contents to LLA).

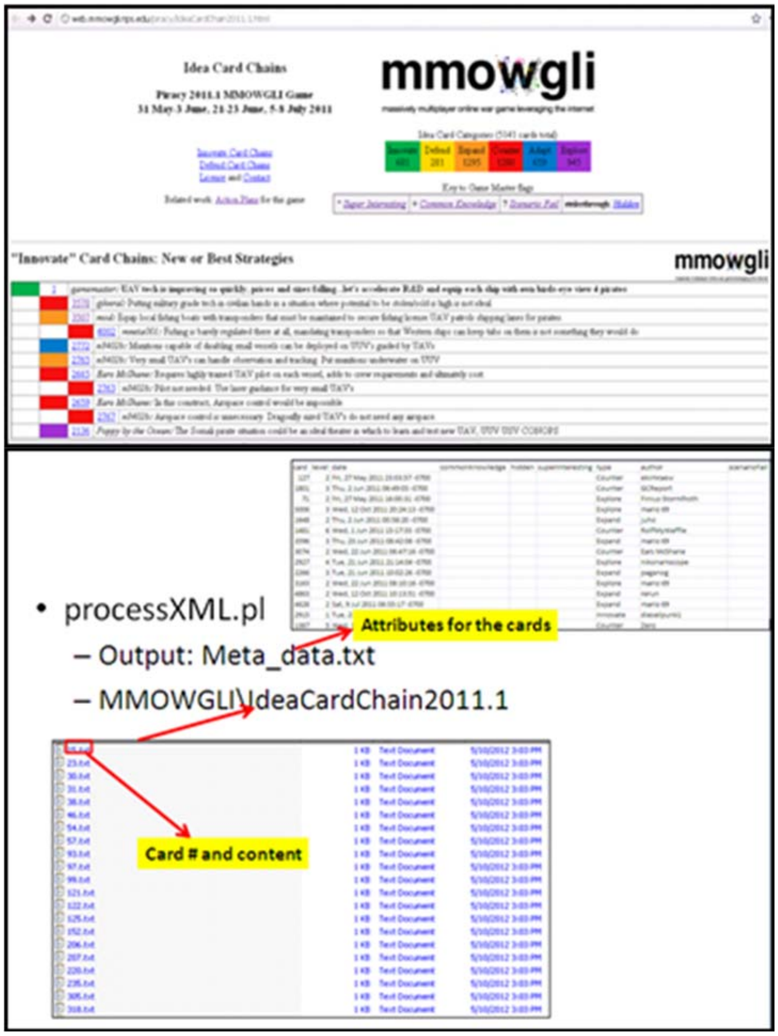

Figure 4. Idea Cards Transformed to LLA Inputs (e.g., a Directory With Files of Content of the Cards and Attributes, meta_data.txt)

There are two steps used in LLA to discover themes. A theme is a cluster of related word pairs:

- 1st Iteration (Figure 5 (a)): Compute word pair clusters using Newman community finding algorithm—words as in a community (Girvan & Newman, 2002).
- 2nd Iteration (Figure 5 (b)): Select lexical terms linked to the most central nodes, for example, "fuel, shipboard, liquid."

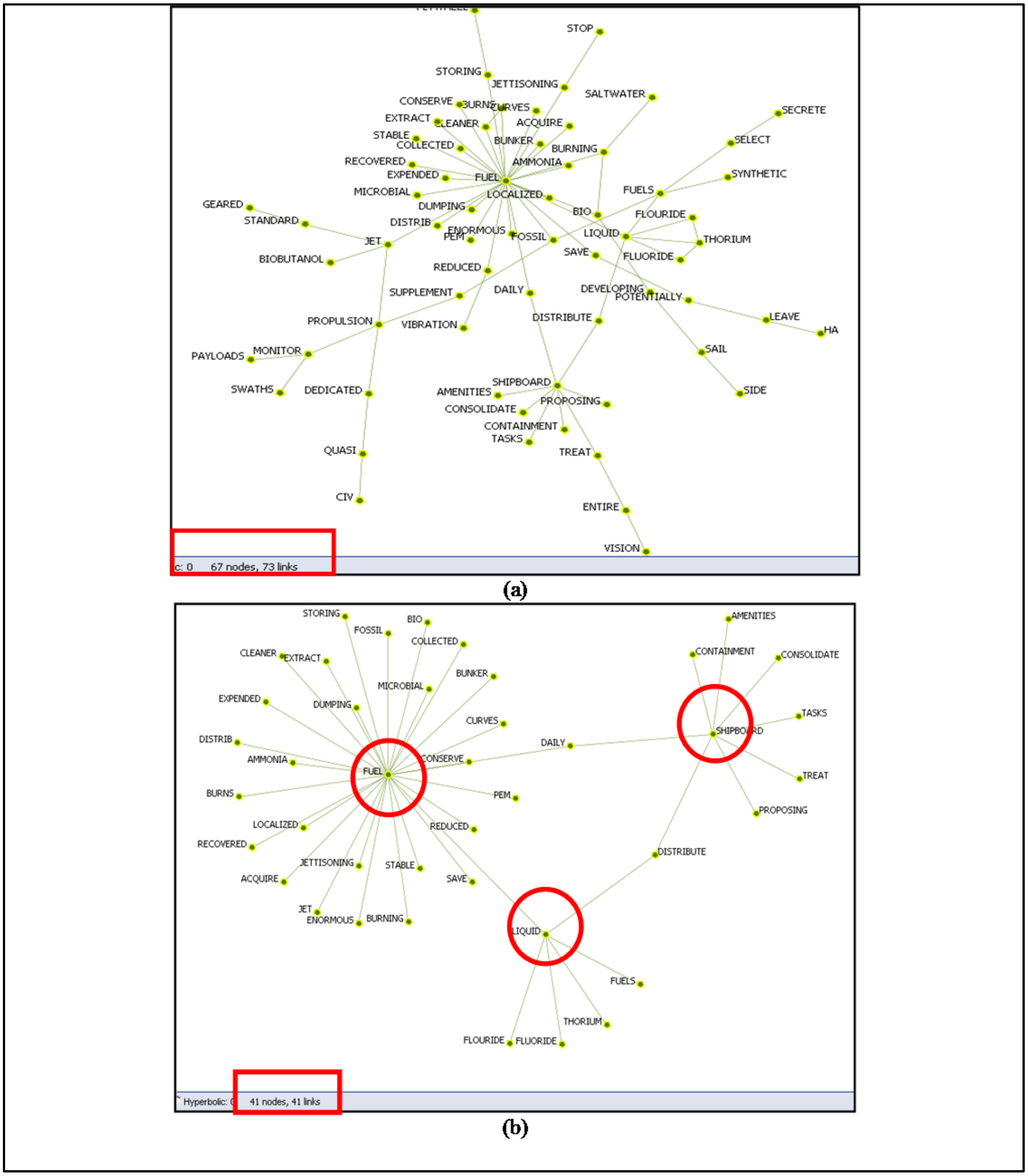

Figure 5. Two Steps LLA Iterations to Group Word Pairs Into Themes

Research Results

As shown in Figure 6, in Phase I, we planned to demonstrate the feasibility of the social media energyMMOWGLI game as an innovation platform that could generate valuable and unexpected contributions and solutions towards the DoD energy efficiency through the acquisition process by linking the current acquisition programs with the energyMMOWGLI game using LLA. We achieved this objective through performing the tasks.

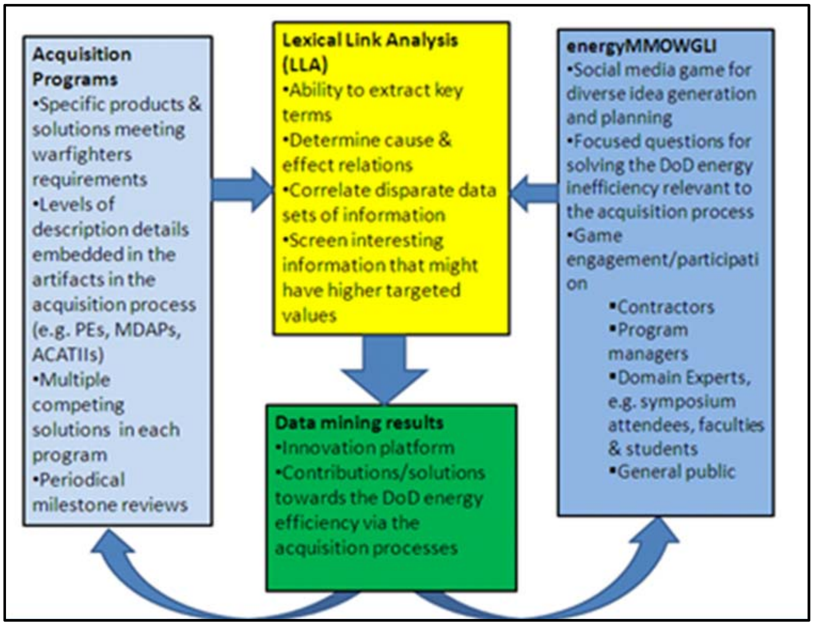

Figure 6. A Glance of the Proposal Objective

Task 1: Prepare Acquisition Data

The goal here is to collate key terms from the current acquisition program in the congressional budget process. The congressional budget process documents (e.g., program elements [PEs] from http://www.dtic.mil/descriptivesum) will be used in this task. This source is the accurate and authoritative high-level artifacts under the DoD Research, Development, Test, and Evaluation (RDT&E). We had analyzed part of these documents in the past (Zhao et al., 2010, 2011a, 2011c, 2012) in detail using the LLA method jointly with other measures such as cost, schedule, and performance.

Specifically, we collected the following most recent (2013) tri-service PE documents for this project:

- http://www.dtic.mil/descriptivesum/Y2013_Navy.html
- http://www.dtic.mil/descriptivesum/Y2013_AirForce.html
- http://www.dtic.mil/descriptivesum/Y2013_Army.html

Task 2: Perform Analysis and Correlation

Compare the already collected energyMMOWGLI results to determine action plan relevance on a program-by-program basis.

We linked the energyMMOWGLI data, specifically, 38 action plans with the PEs prepared in Task 1, and 224 Navy PEs to evaluate the current Navy programs relevant to the game data. Figure 7 shows that the process resulted in a relevance and correlation matrix as illustrated.

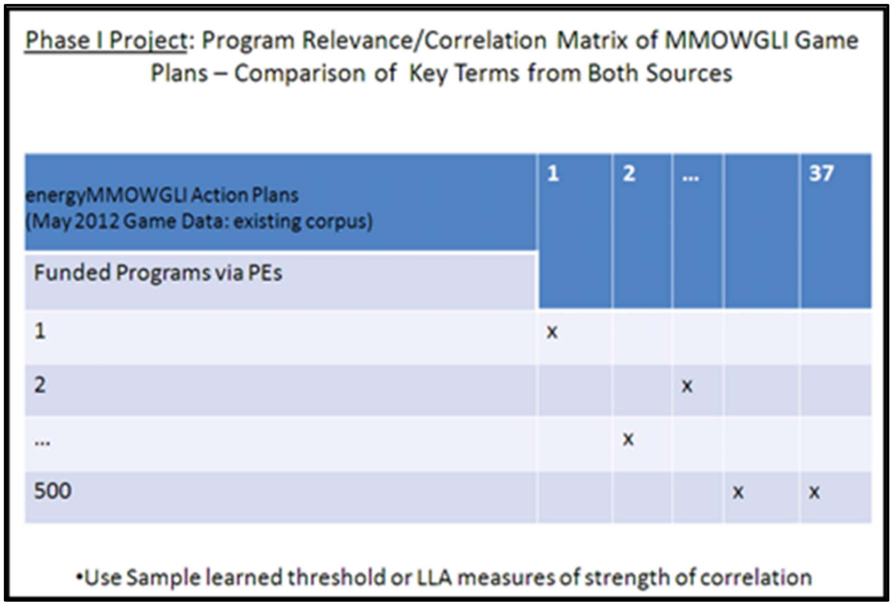

Figure 7. Phase I Relevance Matrix

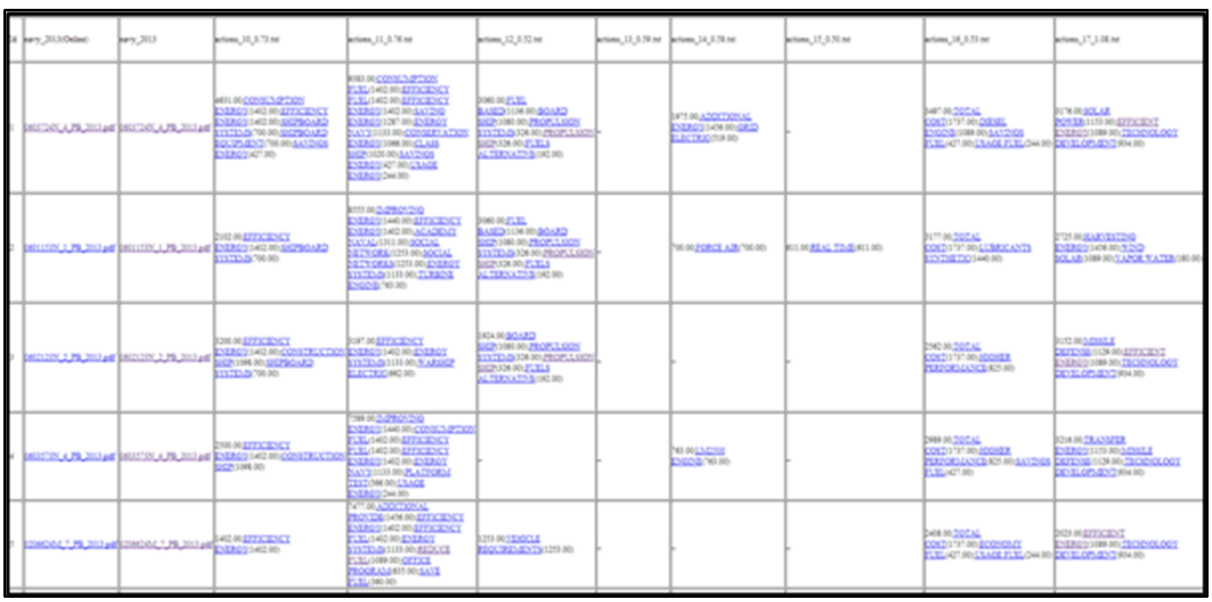

Figure 8. The Overall Match Matrix for the MMOWGLI Energy Game Action Plans and Navy 2013 Program Elements

Figure 8 shows sorted Navy PEs that match the MMOWGLI game data based on a sorted LLA score. The top five most relevant PEs are listed as follows:

- PE 0603724N: Navy Energy Program
- PE 0601153N: Defense Research Sciences
- PE 0602123N: Force Protection Applied Res
- PE 0603573N: Advanced Surface Machinery Sys
- PE 0206624M: Marine Corps Combat Services Support

Clicking on the online link for the top one leads to the online page of the "Navy Energy Program," which is an overall PE specifically focusing on Navy energy issues as shown in Figure 9. This validates that the LLA extracted the relevant keywords from the game data.

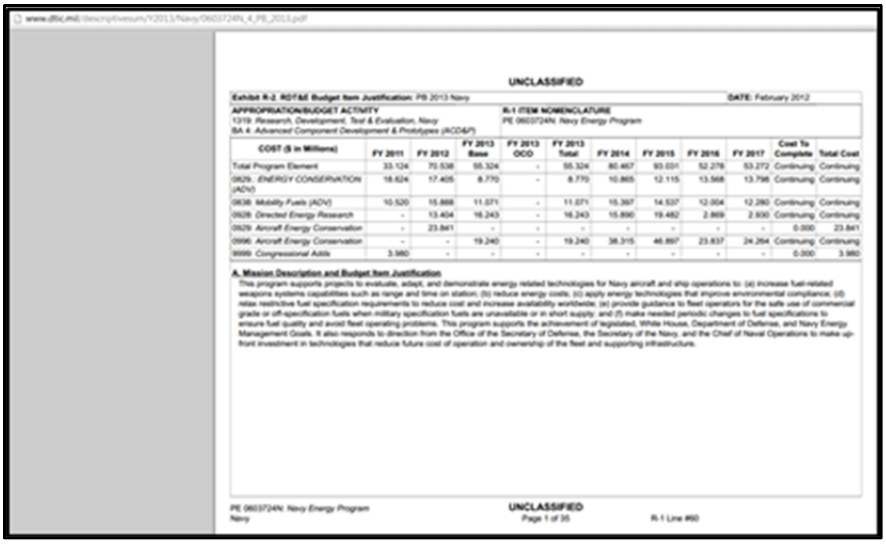

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Exhibit R-2, RDT&E Budget Item Justification: PB 2013 Navy — **DATE:** February 2012

APPROPRIATION/BUDGET ACTIVITY
1319: *Research, Development, Test & Evaluation, Navy*
BA 4: *Advanced Component Development & Prototypes (ACD&P)*

R-1 ITEM NOMENCLATURE
PE 0603724N: *Navy Energy Program*

COST ($ in Millions)	FY 2011	FY 2012	FY 2013 Base	FY 2013 OCO	FY 2013 Total	FY 2014	FY 2015	FY 2016	FY 2017	Cost To Complete	Total Cost
Total Program Element	33.124	70.538	55.324	-	55.324	80.467	93.031	52.279	53.272	Continuing	Continuing
0829: *ENERGY CONSERVATION (ADV)*	18.624	17.405	8.770	-	8.770	10.865	12.115	13.568	13.798	Continuing	Continuing
0838: *Mobility Fuels (ADV)*	10.520	15.888	11.071	-	11.071	15.397	14.537	12.004	12.280	Continuing	Continuing
0928: *Directed Energy Research*	-	13.404	16.243	-	16.243	15.890	19.482	2.869	2.930	Continuing	Continuing
0929: *Aircraft Energy Conservation*	-	23.841	-	-	-	-	-	-	-	0.000	23.841
0996: *Aircraft Energy Conservation*	-	-	19.240	-	19.240	38.315	46.897	23.837	24.264	Continuing	Continuing
9999: *Congressional Adds*	3.980	-	-	-	-	-	-	-	-	0.000	3.980

A. Mission Description and Budget Item Justification
This program supports projects to evaluate, adapt, and demonstrate energy related technologies for Navy aircraft and ship operations to: (a) increase fuel-related weapons systems capabilities such as range and time on station; (b) reduce energy costs; (c) apply energy technologies that improve environmental compliance; (d) relax restrictive fuel specification requirements to reduce cost and increase availability worldwide; (e) provide guidance to fleet operators for the safe use of commercial grade or off-specification fuels when military specification fuels are unavailable or in short supply; and (f) make needed periodic changes to fuel specifications to ensure fuel quality and avoid fleet operating problems. This program supports the achievement of legislated, White House, Department of Defense, and Navy Energy Management Goals. It also responds to direction from the Office of the Secretary of Defense, the Secretary of the Navy, and the Chief of Naval Operations to make up-front investment in technologies that reduce future cost of operation and ownership of the fleet and supporting infrastructure.

PE 0603724N: *Navy Energy Program*
Navy
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R-1 Line #60

Figure 9. Navy Energy Program Element

The matrix in Figure 8 shows a holistic picture of the current acquisition programs in connection with the DoD energy inefficiency situations, efficiency requirements, and possible innovative solutions. Directly looking into the match matrix, as illustrated in Figure 8, can be overwhelming. For that, we applied LLA to discover the themes and divide a single match matrix into many match matrices in different themes. For our research, a theme is a network or community of word pairs that are related to each other. To discover themes, we first applied LLA to compute word pair clusters using Newman community finding algorithm—words as in a community (Girvan & Newman, 2002). There we select lexical terms linked to the most *central* nodes. For example, shown in Figure 11, the red nodes are the most central nodes "environmental, ship, and effective." The red links are the word pairs shared by both sources PEs and MMOWGLI game action plans; the yellow links are the word pairs unique to the game data; and the green ones are those unique to the PEs.

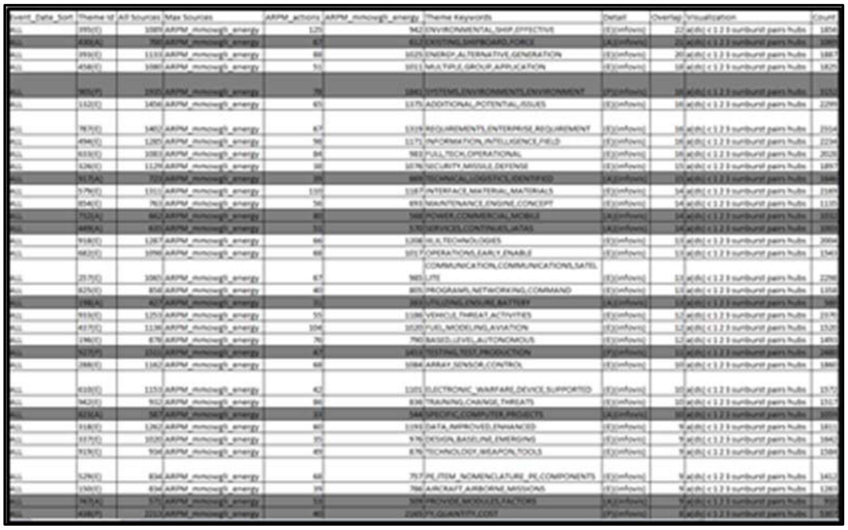

Figure 10. Themes Discovered for Navy 2013 Program Elements Documents and energyMMOWGLI Data, Thresholded and Then Sorted According to the Overlapped Word Pairs From the Two Sources

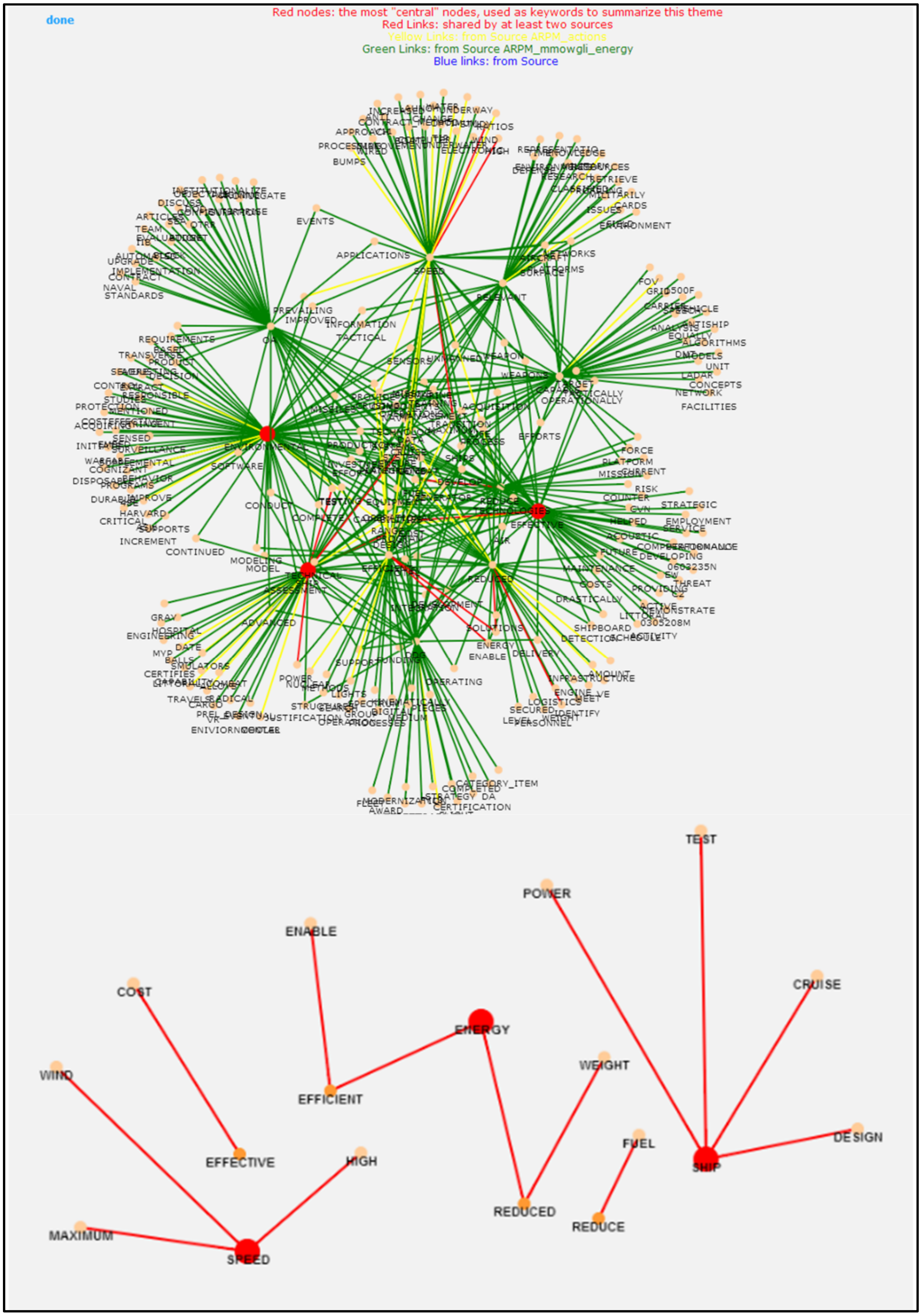

Figure 11. Theme 395(E) Link-Strength Visualizations: "Environmental, Ship, & Effective"

A separate matrix can be constructed for each theme for the word pairs that belongs to only a theme. Figure 12, the correlation matrix for Theme 395(E) labeled as

"environmental, ship, & effective," which has the highest matched word pairs in Figure 12. The matched PEs are sorted according to the number of matched action plans. For example, the top matched PE is "0603724N_PB_2013," titled "Navy Energy Program," indicating that there is a current Navy program dedicated to "energy."

We used this matrix to determine where opportunities reside in the current process to include energy-related elements. Also shown in Figure 12, two concepts, "energy efficient" and "ship design," are dominant in this theme. They are dominant because there are four (4) and two (2) out of 38 action plans contain word pairs "energy efficient" and "ship design," respectively. This seems to suggest that "efficient energy" may have to work with the concept "ship design." However, among the 12 PEs that mentions "ship design," only one entry mentions "energy efficient." This indicates that there is a gap, or a DoD energy inefficiency area, and therefore an opportunity to emphasize the concept "energy efficient" in all the PEs related to the concept "ship design."

PE ID	PE Title	action 26	action 20	action 17	action 28	action 8	action 10	action 11	action 18	action 9	action 5	action 16	action 12	action 7	action 6	# of matched action plans
0603724N_4_PB_2013	Navy Energy Program					ENERGY EFFICIENT		GENERATOR SETS	ENERGY EFFICIENT	SHIP DESIGN	ENERGY EFFICIENT	DIESEL ENGINE			SHIP DESIGN	7
0206624M_7_PB_2013	Marine Corps Cmbt Services Supt			ENERGY EFFICIENT		ENERGY EFFICIENT		REDUCE FUEL	ENERGY EFFICIENT		ENERGY EFFICIENT					5
0601153N_1_PB_2013	Defense Research Sciences	TURBINES GAS	SPEED HIGH							SHIP DESIGN					SHIP DESIGN	4
0206623M_7_PB_2013	MC Ground Cmbt Spt Arms Sys			ENERGY EFFICIENT		ENERGY EFFICIENT			ENERGY EFFICIENT		ENERGY EFFICIENT					4
0602123N_2_PB_2013	Force Protection Applied Res			WIND SOLAR, ENERGY EFFICIENT		ENERGY EFFICIENT			ENERGY EFFICIENT		ENERGY EFFICIENT					4
0603563N_4_PB_2013	Ship Concept Advanced Design		SPEED HIGH							SHIP DESIGN				MAXIMUM SPEED	SHIP DESIGN	4
0602271N_2_PB_2013	Electromagnetic Systems Applied Research			ENERGY EFFICIENT		ENERGY EFFICIENT			ENERGY EFFICIENT		ENERGY EFFICIENT					4
0604567N_5_PB_2013	Ship Contract Design/ Live Fire T&E	TURBINES GAS								SHIP DESIGN					SHIP DESIGN	3
0603721N_4_PB_2013	Environmental Protection									SHIP DESIGN			DIESEL ENGINES		SHIP DESIGN	3
0603561N_4_PB_2013	Advanced Submarine System Development									SHIP DESIGN					SHIP DESIGN	2
0603512N_4_PB_2013	Carrier Systems Development									SHIP DESIGN					SHIP DESIGN	2
0604777N_5_PB_2013	Navigation/Id System									SHIP DESIGN					SHIP DESIGN	2
0605152N_6_PB_2013	Studies & Analysis Supt - Navy									SHIP DESIGN					SHIP DESIGN	2
0204413N_7_PB_2013	Amphibious Tactical Supt Units									SHIP DESIGN					SHIP DESIGN	2
0708730N_7_PB_2013	Maritime Tech (MARITECH									SHIP DESIGN					SHIP DESIGN	2
0605866N_6_PB_2013	Navy Space & Electr Warfare Supt									SHIP DESIGN					SHIP DESIGN	2
0603236N_3_PB_2013	Warfighter Sustainment Advd Tech		1													1
0603673N_3_PB_2013	Future Naval Capabilities Advanced Tech Dev		SPEED HIGH													1
0603640M_3_PB_2013	MC Advanced Technology Demo				GENERATOR TURBINE											1
0602114N_2_PB_2013	Power Proj Applied Research	TURBINES GAS														1
0205633N_7_PB_2013	Aviation Improvements												DIESEL ENGINES			1
0604258N_6_PB_2013	Target Systems Development													MAXIMUM SPEED		1
0603658N_4_PB_2013	Cooperative Engagement						REDUCED WEIGHT									1
0603758N_3_PB_2013	Navy Warfighting Exp & Demo										REDUCED ENERGY					1
0602236N_2_PB_2013	Warfighter Sustainment Applied Res		SPEED HIGH				REDUCED WEIGHT									1
0603573N_4_PB_2013	Advanced Surface Machinery Sys	SHIP POWER														1
0603564N_4_PB_2013	Ship Prel Design & Feasibility Studies		SPEED HIGH													1
0208058N_7_PB_2013	Joint High Speed Vessel (JHSV)		SPEED HIGH													1
0305160N_7_PB_2013	Navy Meteorological and Ocean Sensors-Space(METOC)		SPEED WIND													1

Figure 12. Match Matrix for Theme 395(E)

Following the same analysis, Appendix A lists more gap and opportunity areas discovered by LLA.

In the near future, we will engage the students, faculties, and a wide acquisition research community to continue the discussion of the DoD energy efficiency and possible solutions through series of planned MMOWGLI games (MMOWGLI Energy Game Portal, 2012). As possible acquisition professionals being Game Masters, the brainstorming and discussions can be steered towards more specific requirements, for example, the ones below:

1. How to provide operational forces greater flexibility and reduce their dependency on logistics infrastructure.
2. How to change the DoD's current requirements and acquisition processes so they do not undervalue technologies with the potential to improve energy efficiency.

The results from the match matrices can be recommended areas for the seed questions for a MMOWGLI energy game.

Conclusions

Multiple useful conclusions of broad applicability arise from this work.

- We demonstrated the use of the MMOWGLI social media brainstorming platform and LLA as a combined collective intelligence platform to gather consensus via the MMOWGLI energy game and match data using LLA, with the current existing DoD programs, derived from Navy 2013 PEs documents.
- We identified critical variables, elements, concepts, or word pairs that can be linked to Navy energy efficiency within and among numerous programs.
- We used match matrices for each individual theme found through LLA to identify energy-related parameters or elements as word pairs, and then we used these word pairs to further identify opportunities in the current process, (i.e., what PEs might be good candidates to engage the energy-related action plans discussed in the MMOWGLI energy game?).
- We found that the great majority of Navy programs are affected by (or even critically dependent on) energy issues, but goals and even terms are handled inconsistently.

Therefore, without imposing significant operational burdens and vulnerabilities, innovative "energy efficiency" ideas from the social media game might be quickly and naturally implemented into the current processes that drive force structures, combat operations, logistics, and acquisition decisions.

The resulting capability, the automation of LLA computations and an analyst interface for report generation, demonstrate MMOWGLI together with LLA as an important tool throughout the longer life cycle of the acquisition process for incorporating the "fully burdened cost of fuel" into acquisition analyses.

Recommendations for Future Work

Much work can continue; specifically, we see excellent potential in the following:

- Crowd sourcing to provide meaningful feedback on either cross-cutting themes (such as energy reduction/efficiency) or specific acquisition programs.
    - For example, acquisition experts might participate in the Business Innovation Initiative (bii) MMOWGLI Game Round 2 in summer 2013 to gain further experience in relevant crowd-sourcing capabilities.
- Building MMOWGLI game infrastructure in tandem with LLA computational structure to reduce manual labor and maximize analyst flexibility with each round.
- Continuing work on real datasets that spurs meaningful (rather than toy or contrived) analysis, and producing further data visualizations tuned to support focused analytic queries by players and decision-makers.
- Maintaining backwards compatibility among games to enable steady growth via the available corpus and products each year. This further enables longitudinal analysis and observability of trends and evolution over time.
- Stabilizing the data-model design of LLA computational products, which may enable future visualization improvements to be directly applied to past products.
- Speedier production of LLA products that can influence fast-react game rounds or program changes as they proceed, rather than after the event. We

want to reduce analysis cycles from weeks to days, and even to hours, approaching real time.

- Program-support brainstorming and collective intelligence experiments that should continue, both for proposed and current programs of record. Games + link analysis, connecting the record of "what is reported being done" with "what do people think," all help normalize the use of concept terminology and also identify unsuspected applicability of new breakthrough capabilities.
- Overall progress and process improvements that may now be measured so that causes and effects of improvements in acquisition system cost-effectiveness and responsiveness are documented.
- Navy strategies for improving energy efficiency needs to be handled consistently across programs. Terms of reference, metrics, and opportunities all need to be addressed consciously and consistently.
- Following a series of deliberate experiments, long-term procedural improvements to the formal milestone acquisition process can be considered. For example:
    - Are program terms of reference consistent with DoD-wide best practice?
    - Are all applicable energy reduction and energy efficiency techniques identified?
    - Routine crowd sourcing as due diligence: subject-matter expert and public reviews (as appropriate) to accompany milestone decisions.
    - Has in-game or post-game analysis identified synergies among different programs that deserve further investigation?
- Open question: How can these tools statistically identify discussions that are focused on concepts in novel combinations? In other words, are they "on topic" but not explicitly addressed by the reference documents? These are the discussions where significant innovation may be occurring.
- Improving the defense acquisition process is a major challenge that holds potentially massive payoffs. Decision-milestone preparations can benefit from broader review and judicious cross-program comparisons that discover possibilities that aren't already recognized. Future rounds of the BII MMOWGLI game will continue investigating how crowd-sourcing techniques might best be applied to make a good acquisition process even better.

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Appendix A: Gaps and Opportunity Areas to Integrate the Innovative Concepts and Action Plans From the MMOWGLI Energy Game Into Current Navy Program Elements

"Fuel," as an independent variable, can be crucial for improving DoD energy efficiency. For example, according to the DoD energy inefficiency report (DoD Acquisition Technology, 2012),

> The current process either does not consider fuel, or considers only the commodity price. However, moving fuel into and around the theater of combat imposes significant operational burdens and vulnerabilities, drives force structure toward support at the expense of combat operations, and increases costs for delivery and logistics. Neither current requirements nor acquisition processes accurately explore tradeoff opportunities using fuel as an independent variable. This prevents an end-to-end view of fuel utilization

and distorts platform design choices, consequently preventing DoD from achieving maximum combat benefit for its logistics effort.

We argue that by matching the data and consensus gathered from the collective intelligence platform (e.g., MMOWGLI energy game data with the current existing DOD programs, exemplified in the Navy 2013 PEs documents), we can identify critical variables, elements, concepts or word pairs that are linked to energy. Therefore, without imposing significant operational burdens and vulnerabilities, innovative "energy efficiency" ideas from the game might be naturally implemented into the current processes that drives force structures, combat operations, delivery, and logistics.

We use match matrices for each individual theme found through LLA to identify energy-related parameters or elements as word pairs, and then we use these word pairs to identify the opportunities in the current process (i.e., what PEs might be good candidates to engage the energy-related parameters/elements/concepts/word pairs discussed in the MMOWGLI energy game). These findings are listed below.

Id	navy_2013(Online)	actions_10_0.73.txt	actions_18_0.71.txt	actions_26_1.44.txt	Total Row LLA Score
3	0603724N_4_PB_2013.pdf	SHIPBOARD SYSTEMS;SHIPBOARD EQUIPMENT	_	EXISTING FLEET	2100
5	0604777N_5_PB_2013.pdf	SHIPBOARD SYSTEMS	_	EXISTING FLEET	1400
6	0603512N_4_PB_2013.pdf	SHIPBOARD EQUIPMENT;SHIPBOARD SYSTEMS	_	_	1400
7	0205633N_7_PB_2013.pdf	_	SECONDARY POWER	_	1400
9	0604567N_5_PB_2013.pdf	SHIPBOARD SYSTEMS	_	SHIPBOARD SYSTEM	1400
12	0601153N_1_PB_2013.pdf	SHIPBOARD SYSTEMS	_	_	1400
15	0603581N_4_PB_2013.pdf	SHIPBOARD SYSTEMS	_	SHIPBOARD SYSTEM	1400
16	0603721N_4_PB_2013.pdf	SHIPBOARD SYSTEMS	_	_	1400
34	0604402N_7_PB_2013.pdf	SHIPBOARD SYSTEMS	_	_	700
41	0205620N_7_PB_2013.pdf	_	_	SHIPBOARD SYSTEM	700
43	0602123N_2_PB_2013.pdf	SHIPBOARD SYSTEMS	_	_	700
51	0603513N_4_PB_2013.pdf	_	_	SHIPBOARD SYSTEM	700
55	0603795N_4_PB_2013.pdf	_	_	SHIPBOARD SYSTEM	700
57	0603739N_4_PB_2013.pdf	SHIPBOARD EQUIPMENT	_	_	700

The match matrix for Theme 430 suggests that PEs mentioned the concepts "existing fleet," "shipboard system(s)," "shipboard equipment," and "secondary power" that might have the overall potential to engage Action Plans 10, 26, and 18.

- Action Plan 10: In this era of convergence, reduce the number of shipboard systems and focus more on small computers with high capability (Android, iOS apps).
- Action Plan 26: Expand the use of nuclear power in the fleet and ashore.
- Action Plan 18: Offshore basing.

id	navy_2013(Online)	actions_10_0.73.txt	actions_11_0.76.txt	actions_17_1.08.txt	actions_18_0.71.txt	actions_22_0.63.txt	actions_28_0.86.txt	actions_34_1.00.txt	actions_35_0.82.txt	Total Row LLA Score
1	0603724N_4_PB_2013.pdf		ENERGY NAVY		ALTERNATIVE FUEL GENERATION POWER ALTERNATIVE ENERGY RENEWABLE SOURCES	RENEWABLE ENERGY		COSTS ENERGY	ALTERNATIVE FUEL	29793
2	0601153N_1_PB_2013.pdf		ENERGY SYSTEMS		ALTERNATIVE FUEL GENERATION POWER	RENEWABLE ENERGY			ALTERNATIVE FUEL	11330
3	0602123N_2_PB_2013.pdf		ENERGY SYSTEMS		GENERATION POWER ALTERNATIVE ENERGY					10197
4	0602131M_2_PB_2013.pdf				ALTERNATIVE FUEL GENERATION POWER				ALTERNATIVE FUEL	9064
5	0603573N_4_PB_2013.pdf		ENERGY NAVY		GENERATION POWER					9064
6	0206624M_7_PB_2013.pdf		ENERGY SYSTEMS		GENERATION POWER	RENEWABLE ENERGY				7931
7	0603640M_3_PB_2013.pdf				GENERATION POWER RENEWABLE SOURCES					6798
8	0601152N_1_PB_2013.pdf				GENERATION POWER					4532
9	0604567N_5_PB_2013.pdf				GENERATION POWER					4532
10	0604274N_5_PB_2013.pdf				GENERATION POWER					4532
11	0603758N_3_PB_2013.pdf				GENERATION POWER					4532
12	0603236N_3_PB_2013.pdf				GENERATION POWER					4532
13	0604512N_5_PB_2013.pdf									2266
14	0206623M_7_PB_2013.pdf					RENEWABLE ENERGY				2266
15	0206313M_7_PB_2013.pdf		ENERGY SYSTEMS							2266
16	0602747N_2_PB_2013.pdf					KINETIC ENERGY				1133
17	0605013M_5_PB_2013.pdf									1133
18	0303140N_7_PB_2013.pdf	MACHINE VIRTUAL								1133
19	0304785N_5_PB_2013.pdf									1133
20	0604280N_5_PB_2013.pdf									1133
21	0602271N_2_PB_2013.pdf									1133
22	0603502N_4_PB_2013.pdf									1133
23	0604376M_5_PB_2013.pdf									1133
24	0604262N_5_PB_2013.pdf									1133
25	0603237N_4_PB_2013.pdf	MACHINE VIRTUAL								1133
26	0605853N_6_PB_2013.pdf									1133
27	0603831M_4_PB_2013.pdf									1133
28	0604270N_5_PB_2013.pdf									1133
29	0605873M_6_PB_2013.pdf									1133
30	0206625M_7_PB_2013.pdf			STATION BASE						1133
31	0604231N_5_PB_2013.pdf						COSTS INFRASTRUCTURE			1133
32	0602750N_2_PB_2013.pdf		ENERGY SYSTEMS							1133
33	0605154N_6_PB_2013.pdf									1133
34	0604800N_5_PB_2013.pdf									1133
35	0604717M_7_PB_2013.pdf									1133
36	0603635M_4_PB_2013.pdf									1133
37	0605812M_6_PB_2013.pdf									1133

The match matrix for Theme 393 suggests that the PEs with the concepts "Navy energy," "energy systems," "power generation," "alternative fuel," "alternative energy," "renewable sources," and "costs—energy/infrastructure" could be used good candidates to implement the innovative ideas related to Action Plans 11, 18, 22, and 35.

- Action Plan 11: Enhanced education to develop an energy efficient fleet.
- Action Plan 18: Offshore basing.
- Action Plan 22: Scaling the small solutions: Energy recycling and rethinking "The Big Fix."

id	navy_2013(Online)	actions_10_0.73.txt	actions_12_0.52.txt	actions_15_0.50.txt	actions_22_0.63.txt	actions_25_0.88.txt	actions_26_1.44.txt	actions_32_0.50.txt	actions_4_0.76.txt	actions_5_0.56.txt	Total Row LLA Score
2	0604231N_5_PB_2013.pdf			EXPEDITIONARY NAVAL	ACTION ITEMS		STRIKE CARRIER				4320
3	0603724N_4_PB_2013.pdf		BOARD SHIP				STRIKE CARRIER			DASHBOARD ENERGY	3240
4	0206624M_7_PB_2013.pdf				OPERATING TIME				OPERATING TIME		2160
5	0603542N_4_PB_2013.pdf		BOARD SHIP						APPLICATION MILITARY		2160
8	0604311N_5_PB_2013.pdf			EXPEDITIONARY NAVAL							1080
9	0603512N_4_PB_2013.pdf						STRIKE CARRIER				1080
10	0205633N_7_PB_2013.pdf							BOARD EQUIPMENT			1080
11	0603582N_4_PB_2013.pdf						STRIKE CARRIER				1080
13	0602782N_2_PB_2013.pdf					OPERATING NETWORK					1080
14	0604280N_5_PB_2013.pdf	MULTIPLE HARDWARE									1080
15	0604234N_5_PB_2013.pdf						STRIKE CARRIER				1080
16	0205658N_7_PB_2013.pdf						STRIKE CARRIER				1080
17	0604216N_5_PB_2013.pdf						STRIKE CARRIER				1080
18	0605152N_6_PB_2013.pdf						STRIKE CARRIER				1080
19	0603261N_4_PB_2013.pdf						STRIKE CARRIER				1080
20	0601153N_1_PB_2013.pdf		BOARD SHIP								1080
21	0602123N_2_PB_2013.pdf		BOARD SHIP								1080
22	0204152N_7_PB_2013.pdf						STRIKE CARRIER				1080
23	0602750N_2_PB_2013.pdf			EXPEDITIONARY NAVAL							1080
24	0602131M_2_PB_2013.pdf			EXPEDITIONARY NAVAL							1080
25	0603581N_4_PB_2013.pdf						STRIKE CARRIER				1080
26	0604230N_5_PB_2013.pdf			EXPEDITIONARY NAVAL							1080
27	0603640M_3_PB_2013.pdf			EXPEDITIONARY NAVAL							1080
28	0603235N_3_PB_2013.pdf			EXPEDITIONARY NAVAL							1080
29	0603755N_4_PB_2013.pdf						STRIKE CARRIER				1080
30	0604212N_5_PB_2013.pdf						STRIKE CARRIER				1080

The match matrix for Theme 458 shows that the PEs mentioned ("naval expeditionary," "ship board," and "strike carrier") can good candidates to engage Action Plans 15 and 26.

- Action 15: A global navy formed by an alliance of nation linked in real time. That way the nearest force will response and reduce travel distances.
- Action 26: Expand use of nuclear power in the fleet.

Related concepts include "multiple hardware," "operating time," and "dashboard energy."

Id	navy_2013(Online)	actions_18_0.71.txt	actions_19_0.33.txt	actions_20_1.14.txt	actions_26_1.44.txt	actions_31_1.10.txt	actions_35_0.82.txt	actions_4_0.76.txt	actions_7_0.51.txt	Total Row LLA Score
1	0603721N_4_PB_2013.pdf		TREATMENT WATER	SHIPS SURFACE			TREATMENT WATER		SHIPS SURFACE	7740
2	0603114N_3_PB_2013.pdf			SHIPS SURFACE		ENVIRONMENT OPERATIONAL			SHIPS SURFACE	5805
3	0604567N_5_PB_2013.pdf			SHIPS SURFACE		ENVIRONMENT OPERATIONAL			SHIPS SURFACE	5805
4	0602123N_2_PB_2013.pdf	UNMANNED SYSTEMS		SHIPS SURFACE					SHIPS SURFACE	5805
5	0603563N_4_PB_2013.pdf			SHIPS SURFACE	BUILT PURPOSE				SHIPS SURFACE	5805
6	0603573N_4_PB_2013.pdf			SHIPS SURFACE,AUXILIARY PROPULSION					SHIPS SURFACE	5805
7	0204229N_7_PB_2013.pdf			SHIPS SURFACE					SHIPS SURFACE	3870
8	0603925N_4_PB_2013.pdf			SHIPS SURFACE					SHIPS SURFACE	3870
9	0204228N_7_PB_2013.pdf			SHIPS SURFACE					SHIPS SURFACE	3870
10	0602271N_2_PB_2013.pdf			SHIPS SURFACE					SHIPS SURFACE	3870
11	0603502N_4_PB_2013.pdf			SHIPS SURFACE					SHIPS SURFACE	3870
12	0204574N_7_PB_2013.pdf			SHIPS SURFACE					SHIPS SURFACE	3870
13	0603261N_4_PB_2013.pdf	UNMANNED SYSTEMS				ENVIRONMENT OPERATIONAL				3870
14	0603542N_4_PB_2013.pdf				POWERED NUCLEAR,POWERED SHIPS					3870
15	0604518N_5_PB_2013.pdf			SHIPS SURFACE					SHIPS SURFACE	3870
16	0604256N_6_PB_2013.pdf			SHIPS SURFACE					SHIPS SURFACE	3870
17	0603123N_3_PB_2013.pdf			SHIPS SURFACE					SHIPS SURFACE	3870
18	0603513N_4_PB_2013.pdf			SHIPS SURFACE					SHIPS SURFACE	3870
19	0603860N_4_PB_2013.pdf			SHIPS SURFACE					SHIPS SURFACE	3870
20	0603640M_3_PB_2013.pdf	UNMANNED SYSTEMS				ENVIRONMENT OPERATIONAL				3870
21	0604771N_5_PB_2013.pdf									3870
22	0604231N_5_PB_2013.pdf			SHIPS SURFACE					SHIPS SURFACE	3870
23	0602236N_2_PB_2013.pdf		TREATMENT WATER				TREATMENT WATER			3870
24	0602747N_2_PB_2013.pdf	UNMANNED SYSTEMS								1935
25	0303140N_7_PB_2013.pdf					ENVIRONMENT OPERATIONAL				1935
26	0305160N_7_PB_2013.pdf					ENVIRONMENT OPERATIONAL				1935
27	0604756N_5_PB_2013.pdf					ENVIRONMENT OPERATIONAL				1935
28	0601152N_1_PB_2013.pdf	UNMANNED SYSTEMS								1935
29	0206624M_7_PB_2013.pdf					ENVIRONMENT OPERATIONAL				1935
30	0604707N_4_PB_2013.pdf	UNMANNED SYSTEMS								1935
31	0206623M_7_PB_2013.pdf					ENVIRONMENT OPERATIONAL				1935
32	0605853N_6_PB_2013.pdf	UNMANNED SYSTEMS								1935
33	0204311N_7_PB_2013.pdf				POWERED NUCLEAR					1935
34	0204413N_7_PB_2013.pdf							POWERED SOLAR		1935
35	0603254N_4_PB_2013.pdf				POWERED NUCLEAR					1935
36	0606013N_5_PB_2013.pdf					ENVIRONMENT OPERATIONAL				1935
37	0601153N_1_PB_2013.pdf	UNMANNED SYSTEMS								1935
38	0603782N_3_PB_2013.pdf	UNMANNED SYSTEMS								1935
39	0305237N_7_PB_2013.pdf	UNMANNED SYSTEMS								1935
40	0602750N_2_PB_2013.pdf					ENVIRONMENT OPERATIONAL				1935
41	0604404N_5_PB_2013.pdf	UNMANNED SYSTEMS								1935
42	0603581N_4_PB_2013.pdf	UNMANNED SYSTEMS								1935
43	0603758N_3_PB_2013.pdf	UNMANNED SYSTEMS								1935
44	0604218N_5_PB_2013.pdf	UNMANNED SYSTEMS								1935
45	0603561N_4_PB_2013.pdf	UNMANNED SYSTEMS								1935
46	0605863N_6_PB_2013.pdf					ENVIRONMENT OPERATIONAL				1935
47	0602435N_2_PB_2013.pdf					ENVIRONMENT OPERATIONAL				1935

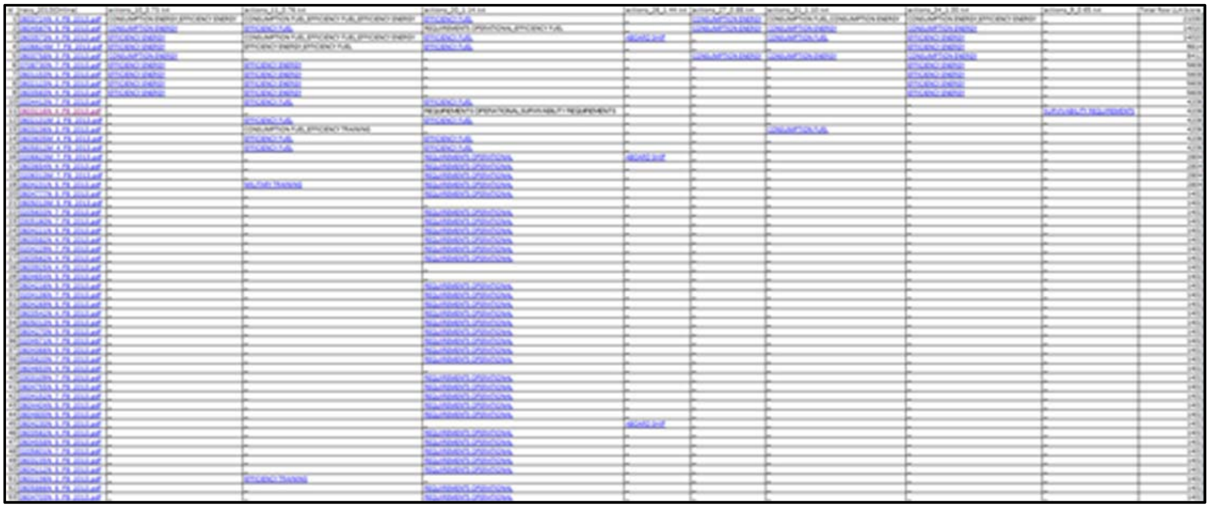
The matrix for Theme 905 that the PEs involved ("unmanned systems," "surface ships," "nuclear powered," "operational environment," and "water treatment") can be good candidates for engaging Action Plans 18, 19, 20, 26, 31, 35, 4, and 7.

- Action Plan 18: Offshore basing.
- Action Plan 19: Implement self-sustaining support infrastructure on all Navy bases.
- Action Plan 20: Sails on vessels; use sails that are foldable on the sides of vessels.
- Action Plan 26: Expand the use of nuclear power in the fleet and ashore.
- Action Plan 31: Add "reducing energy consumption" to Battle E criteria.
- Action Plan 35: Create 3D/vertical farms for use in growing biofuels and crop for human consumption.
- Action Plan 4: Change small land vehicle transportation to hybrid vehicles in non-combat capacity.
- Action Plan 7: Install "sea brakes" that generate electricity, like a Prius. These could be used to aid in docking/slowing ships and reduce the need for tugs.

Id	navy_2013(Online)	actions_14_0.58.txt	actions_15_0.50.txt	actions_17_1.08.txt	actions_18_0.71.txt	actions_34_1.00.txt	actions_7_0.51.txt	Total Row LLA Score
1	0603114N_3_PB_2013.pdf	_	_	_	_	_	_	2912
2	0604307N_5_PB_2013.pdf	_	_	_	_	_	_	2912
3	0602271N_2_PB_2013.pdf	_	_	_	_	_	_	2912
4	0206623M_7_PB_2013.pdf	_	_	_	_	_	_	2912
5	0601153N_1_PB_2013.pdf	_	_	HARVESTING ENERGY	HARVESTING ENERGY	_	_	2912
6	0603724N_4_PB_2013.pdf	ADDITIONAL ENERGY	_	_	_	POTENTIAL ENERGY	_	2912
7	0603673N_3_PB_2013.pdf	_	_	HARVESTING ENERGY	HARVESTING ENERGY	_	_	2912
8	0603635M_4_PB_2013.pdf	_	_	_	_	_	_	2912
9	0603640M_3_PB_2013.pdf	_	FORCES GROUND	_	_	_	_	2912
10	0605812M_4_PB_2013.pdf	_	_	_	_	_	_	2912
11	0604501N_5_PB_2013.pdf	_	_	_	_	_	_	2912
12	0602236N_2_PB_2013.pdf	_	_	HARVESTING ENERGY	HARVESTING ENERGY	_	_	2912
13	0605013M_5_PB_2013.pdf	_	FORCES GROUND	_	_	_	_	1456
14	0303140N_7_PB_2013.pdf	_	_	_	_	_	_	1456
15	0604258N_6_PB_2013.pdf	_	_	_	_	_	_	1456
16	0602235N_2_PB_2013.pdf	_	_	_	_	_	_	1456
17	0603582N_4_PB_2013.pdf	_	_	_	_	_	_	1456
18	0604761N_5_PB_2013.pdf	_	_	_	_	_	_	1456
19	0605867N_6_PB_2013.pdf	_	_	_	_	_	_	1456
20	0604757N_5_PB_2013.pdf	_	_	_	_	_	_	1456
21	0205658N_7_PB_2013.pdf	_	_	_	_	_	_	1456
22	0206624M_7_PB_2013.pdf	_	_	_	_	_	_	1456
23	0101221N_7_PB_2013.pdf	_	_	_	_	_	_	1456
24	0603261N_4_PB_2013.pdf	_	_	_	_	_	_	1456
25	0204571N_7_PB_2013.pdf	_	_	_	_	_	_	1456
26	0604366N_5_PB_2013.pdf	_	_	_	_	_	_	1456
27	0205620N_7_PB_2013.pdf	_	_	_	_	_	_	1456
28	0303109N_7_PB_2013.pdf	_	_	_	_	_	_	1456
29	0602123N_2_PB_2013.pdf	_	_	_	_	_	HYDRODYNAMIC FORCES	1456
30	0603782N_3_PB_2013.pdf	_	_	_	_	_	_	1456
31	0604755N_5_PB_2013.pdf	_	_	_	_	_	_	1456
32	0206313M_7_PB_2013.pdf	_	FORCES GROUND	_	_	_	_	1456
33	0204152N_7_PB_2013.pdf	_	_	_	_	_	_	1456
34	0602750N_2_PB_2013.pdf	_	FORCES GROUND	_	_	_	_	1456
35	0602131M_2_PB_2013.pdf	_	FORCES GROUND	_	_	_	_	1456
36	0604404N_5_PB_2013.pdf	_	FORCES GROUND	_	_	_	_	1456
37	0702239N_7_PB_2013.pdf	_	_	_	_	_	_	1456
38	0604230N_5_PB_2013.pdf	_	_	_	_	_	_	1456
39	0603860N_4_PB_2013.pdf	_	_	_	_	_	_	1456
40	0602114N_2_PB_2013.pdf	_	_	_	_	_	_	1456
41	0603721N_4_PB_2013.pdf	_	_	_	_	_	_	1456
42	0604231N_5_PB_2013.pdf	_	_	_	_	_	_	1456
43	0603207N_4_PB_2013.pdf	_	_	_	_	_	_	1456
44	0603235N_3_PB_2013.pdf	_	_	_	_	_	_	1456
45	0603747N_3_PB_2013.pdf	_	_	_	_	_	_	1456
46	0804758N_6_PB_2013.pdf	_	_	_	_	_	_	1456

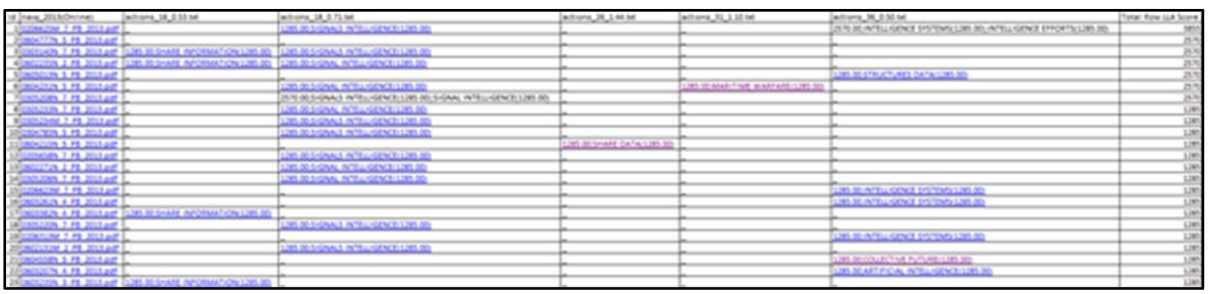
The match matrix for Theme 132 shows that the PEs mentioned ("additional energy," "ground forces" [e.g., PE 0602131M, PE 0603640M; PE 0206313M; PE 0602750N; PE 0605013M; PE 0604404N], "harvesting energy" [e.g., PE 0602236N: Warfighter Sustainment Applied Res; PE 0603673N: (U)Future Naval Capabilities Advanced Tech Dev; PE 0601153N: Defense Research Sciences; PE 0602123N: Force Protection Applied Res], "potential energy," and "hydrodynamic forces") are the good candidates to engage Action Plans 14, 15, 17, 18, 34, and 7.

- Action Plan 14: Recycle everything biological into fuel: waste, etc.
- Action Plan 15: A global navy formed by an alliance of nation linked in real time. That way, the nearest force will response and reduce travel distances.
- Action Plan 17: Energy harvesting satellites in outer space transmit it to Earth via microwave or laser beam.
- Action Plan 18: Create flotillas of ships and sea platforms as off shore bases in critical regions such as the South China Sea.
- Action Plan 34: Create online system or suggestion card system for Navy personnel to input where they see energy savings in their job.
- Action Plan 7: Install "sea brakes" that generate electricity, like a Prius. These could be used to aid in docking/slowing ships, reduce need for tugs.



The match matrix for Theme 787 suggests that the PEs (“energy efficiency” and “fuel efficiency”) can be viewed as “survivability requirements”; therefore, any PEs related to “survivability requirements” (e.g., PE 0603216N: Aviation Survivability) or “operational requirements” can be used to engage Action Plans 10, 11, 20, 27, 31, 34, and 9.

- Action Plan 9: Composite ship design: Explore the use of polymer substrates for improved ship structural design.
- Action Plan 10: In this era of convergence, reduce the number of shipboard systems and focus more on small computers with high capability (Android, iOS apps).



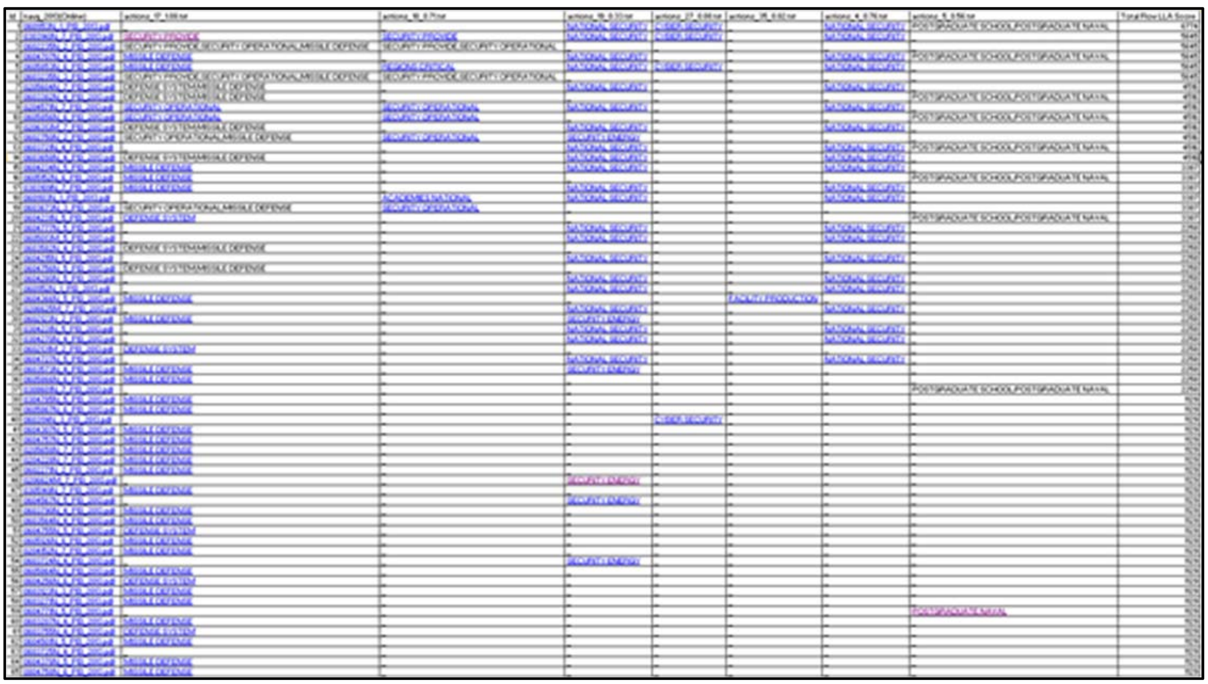
The match matrix for Theme 494 suggests that the PEs mentioned (“shared information,” “signal intelligence,” “share data,” “data structures,” “intelligence systems,” “artificial intelligence,” and “maritime warfare”) might be good candidates to engage Action Plans 16, 18, 26, 31, and 36.

- Action Plan 16: Using synthetic lubricants to save 5% to 25% of energy costs.
- Action Plan 18: Create flotillas of ships and sea platforms as off shore bases in critical regions such as the South China Sea.
- Action Plan 36: Become more efficient at structured, logical dialogue to find the solutions being sought.

Id	navy_2013(Online)	actions_11_0.76.txt	actions_21_0.67.txt	actions_26_1.44.txt	actions_31_1.10.txt	actions_34_1.00.txt	actions_37_3.00.txt	actions_4_0.76.txt	Total Row LLA Score
1	0603542N_4_PB_2013.pdf	_	PLANTS POWER	_	_	_	PLANTS POWER	PLANTS POWER	3249
2	0603747N_3_PB_2013.pdf	TECH ADVANCED	_	GREATER EFFICIENCY	_	GREATER EFFICIENCY	_	_	3249
3	0206624M_7_PB_2013.pdf	_	_	GREATER EFFICIENCY	_	GREATER EFFICIENCY	_	_	2166
4	0604230N_5_PB_2013.pdf	_	_	GREATER EFFICIENCY	_	GREATER EFFICIENCY	_	_	2166
9	0605873M_6_PB_2013.pdf	_	_	_	_	_	_	_	1083
11	0206313M_7_PB_2013.pdf	_	_	_	_	_	_	_	1083
12	0603673N_3_PB_2013.pdf	TECH ADVANCED	_	_	_	_	_	_	1083
13	0603581N_4_PB_2013.pdf	_	_	_	PERIODS EXTENDED	_	_	_	1083
14	0204202N_5_PB_2013.pdf	_	_	_	_	_	_	_	1083
15	0604231N_5_PB_2013.pdf	_	_	_	_	_	_	_	1083
16	0603207N_4_PB_2013.pdf	_	_	_	PERIODS EXTENDED	_	_	_	1083

The match matrix for Theme 633 suggests that the PEs mentioned ("advanced tech" [e.g., PE 0603673N: (U)Future Naval Capabilities Advanced Tech Dev], "greater efficiency" [e.g., PE 0603747N: Undersea Warfare Advanced Tech], and "power plants") can be good candidates to engage Action Plans 11, 21, and 4.

- Action Plan 11: Enhanced education to develop an energy efficient fleet.
- Action Plan 21: DoD shore facility energy independence: Explore use of thorium-based reactors (liquid fluoride thorium reactor [LFTR]) for power generation off the grid.
- Action Plan 4: Change small land vehicle transportation to hybrid vehicles in non-combat capacity.



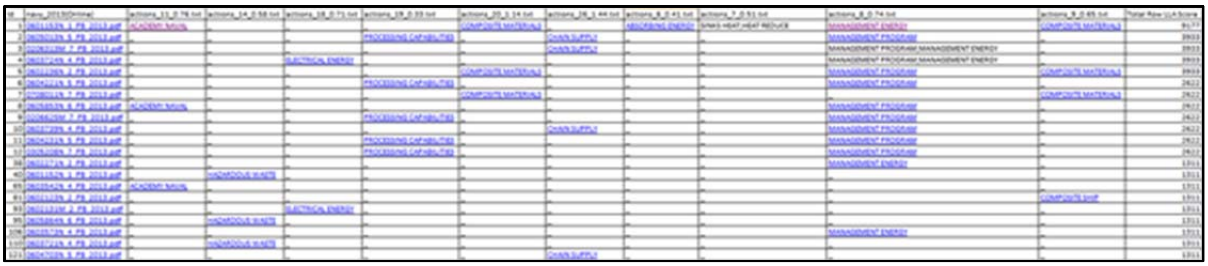
The match matrix for Theme 326 suggests that the PEs mentioned ("energy security," "missile defense," "operational security," "cyber security," "national security," and "Naval Postgraduate School") might be good candidates to engage Action Plans 17, 19, 4, 27, 4, 35, and 5.

- Action Plan 17: Energy harvesting satellites/space-based solar power.
- Action Plan 19: Implement self-sustaining support infrastructure on all Navy bases.
- Action Plan 4: Change small land vehicle transportation to hybrid vehicles in non-combat capacity.

Id	navy_2013(Online)	actions_16_0.53.txt	actions_18_0.71.txt	actions_21_0.67.txt	actions_25_0.88.txt	actions_26_1.44.txt	actions_31_1.10.txt	actions_34_1.00.txt	actions_9_0.65.txt	Total Row LLA Score
1	0603542N_4_PB_2013.pdf	_	NUCLEAR POWER	NUCLEAR POWER	_	NUCLEAR FLEET;NUCLEAR POWER;NUCLEAR NAVAL	_	_	_	3615
2	0603570N_4_PB_2013.pdf	_	NUCLEAR POWER	NUCLEAR POWER	_	NUCLEAR POWER;NUCLEAR TECHNOLOGY	_	_	_	2892
3	0205675N_7_PB_2013.pdf	_	NUCLEAR POWER	NUCLEAR POWER	_	NUCLEAR POWER	_	_	_	2169
4	0206313M_7_PB_2013.pdf	LOGISTICS SYSTEMS	_	_	STANDARDS COMMON	_	LOGISTICS MANAGEMENT	_	_	2169
5	0605013N_5_PB_2013.pdf	LOGISTICS SYSTEMS	_	_	_	_	LOGISTICS MANAGEMENT	_	_	1446
6	0702239N_7_PB_2013.pdf	_	_	_	_	_	LOGISTICS MANAGEMENT	STANDARDS DEVELOPMENT	_	1446
7	0604231N_5_PB_2013.pdf	_	_	_	_	_	LOGISTICS MANAGEMENT	STANDARDS DATA	_	1446
8	0603512N_4_PB_2013.pdf	_	_	_	_	_	LOGISTICS MANAGEMENT	_	_	723
9	0604215N_5_PB_2013.pdf	_	_	_	_	_	_	STANDARDS DEVELOPMENT	_	723
10	0604404N_5_PB_2013.pdf	_	_	_	_	_	LOGISTICS MANAGEMENT	_	_	723
11	0603513N_4_PB_2013.pdf	_	_	_	_	_	_	STANDARDS DEVELOPMENT	_	723
12	0603640M_3_PB_2013.pdf	_	_	_	_	_	_	_	_	723
13	0603561N_4_PB_2013.pdf	_	_	_	_	NUCLEAR TECHNOLOGY	_	_	_	723
14	0603235N_3_PB_2013.pdf	_	_	_	_	_	_	_	STANDARDS SAFETY	723

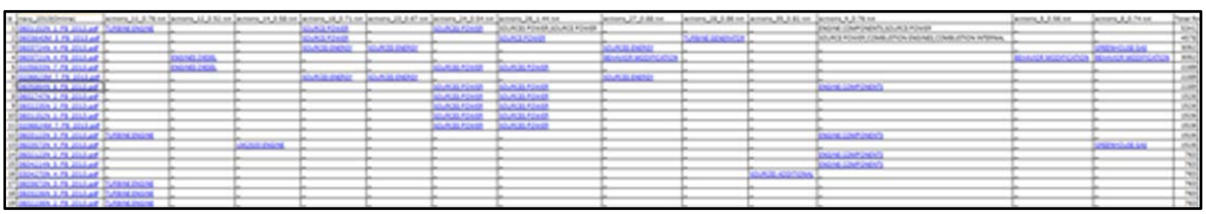
The match matrix for Theme 917 suggests that the PEs mentioned ("nuclear power," "nuclear technology," "safety standards," "logistics systems," "logistics management," "standards development/data," and "common standards") might be good candidates to engage Action Plans 16, 18, 25, 26, 31, 34, and 9.

- Action Plan 34: Create online system or suggestion card system for Navy personnel to input where they see energy savings in their job.



The match matrix for Theme 579 suggests that the PEs mentioned ("energy management," "composite materials," "processing capabilities," "supply chains," "electrical energy," "hazardous waste," "energy absorbing," "sinks heat," "heat reduce," and "naval academy") might be good candidates to engage Action Plans 8, 20, 26, and 9.

- Action Plan 8: Shore energy optimization strategy: Recommendations for improvements and implementation.



The match matrix for Theme 854 suggests that PEs mentioned ("turbine engine," "diesel engine," "energy sources," "power sources," and "greenhouse gas") might be good candidates to engage "behavior modification" related Action Plans 27, 8, and 5.

- Action 27: Upgrade Navy housing with SMART grids to reduce energy consumption. By individualizing electricity/utility bills to single households, family users will be motivated to increase energy saving efforts.
- Action 5: Incentivize behavior to reduce electricity usage in Navy housing.
- Action 8: Update older buildings to be more energy efficient. The Navy is still using buildings that are almost a century old.

These PEs include, for example, PE 0603573N: Advanced Surface Machinery Sys; PE 0603724N: Navy Energy Program; PE 0205633N: Aviation Improvements; PE 0206623M: MC Ground Cmbt Spt Arms Sys; and PE 0605864N: Test & Evaluation Support.

Id	navy_2013(Online)	actions_11_0.76.txt	actions_18_0.71.txt	actions_21_0.67.txt	actions_23_0.67.txt	actions_24_0.54.txt	actions_26_1.44.txt	actions_27_0.88.txt	actions_7_0.51.txt	Total Row LLA Score
1	0602123N_2_PB_2013.pdf	WARSHIP ELECTRIC	_	_	MOBILE POWER	POWER MANAGEMENT	MOBILE POWER	_	SURFACE SHIP	3310
2	0603573N_4_PB_2013.pdf	_	_	SUPPLYING POWER	_	POWER MANAGEMENT	POWER SHIP	_	GENERATING POWER;SURFACE SHIP	3310
3	0206624M_7_PB_2013.pdf	_	_	_	MOBILE POWER	POWER MANAGEMENT	MOBILE POWER	_	_	1986
4	0603114N_3_PB_2013.pdf	_	STORE ENERGY	_	_	_	_	_	SURFACE SHIP	1324
5	0601153N_1_PB_2013.pdf	_	_	_	_	POWER MANAGEMENT	_	_	SURFACE SHIP	1324
6	0602131M_2_PB_2013.pdf	_	_	_	_	POWER MANAGEMENT	_	PEAK POWER	_	1324
7	0602114N_2_PB_2013.pdf	_	_	_	_	_	_	_	SURFACE SHIP	1324
8	0602236N_2_PB_2013.pdf	_	_	_	_	POWER MANAGEMENT	_	_	SURFACE SHIP	1324
9	0602747N_2_PB_2013.pdf	_	_	_	_	_	_	_	SURFACE SHIP	662
10	0604777N_5_PB_2013.pdf	_	_	_	_	_	_	_	SURFACE SHIP	662
11	0604258N_6_PB_2013.pdf	_	_	_	_	_	SURFACE FLEET	_	_	662
12	0602235N_2_PB_2013.pdf	_	_	_	_	_	_	PEAK POWER	_	662
13	0204229N_7_PB_2013.pdf	_	_	_	_	_	_	_	SURFACE SHIP	662
14	0602782N_2_PB_2013.pdf	_	_	_	_	_	_	_	SURFACE SHIP	662
15	0304785N_5_PB_2013.pdf	_	_	_	_	_	SURFACE FLEET	_	_	662
16	0603925N_4_PB_2013.pdf	_	_	_	_	_	_	_	SURFACE SHIP	662
17	0604756N_5_PB_2013.pdf	_	_	_	_	_	SURFACE FLEET	_	_	662
18	0604757N_5_PB_2013.pdf	_	_	_	_	_	_	_	SURFACE SHIP	662
19	0602271N_2_PB_2013.pdf	_	_	_	_	POWER MANAGEMENT	_	_	_	662
20	0601152N_1_PB_2013.pdf	_	_	_	_	_	_	_	SURFACE SHIP	662
21	0604707N_4_PB_2013.pdf	_	_	_	_	_	_	_	SURFACE SHIP	662
22	0605152N_6_PB_2013.pdf	_	_	_	_	_	_	_	SURFACE SHIP	662
23	0603506N_4_PB_2013.pdf	_	_	_	_	_	_	_	SURFACE SHIP	662
24	0603564N_4_PB_2013.pdf	_	_	_	_	_	_	_	SURFACE SHIP	662
25	0205620N_7_PB_2013.pdf	_	_	_	_	_	_	_	SURFACE SHIP	662
26	0605873M_6_PB_2013.pdf	CENTERS TRAINING	_	_	_	_	_	_	_	662
27	0603563N_4_PB_2013.pdf	_	_	_	_	_	_	_	SURFACE SHIP	662
28	0602750N_2_PB_2013.pdf	_	_	_	_	_	_	_	SURFACE SHIP	662
29	0603673N_3_PB_2013.pdf	_	_	_	_	_	_	_	SURFACE SHIP	662
30	0603581N_4_PB_2013.pdf	_	_	_	_	_	SURFACE FLEET	_	_	662
31	0603123N_3_PB_2013.pdf	_	_	_	_	_	_	_	SURFACE SHIP	662
32	0603562N_4_PB_2013.pdf	_	_	_	_	_	_	_	SURFACE SHIP	662
33	0604558N_5_PB_2013.pdf	_	_	_	_	_	_	_	SURFACE SHIP	662
34	0603236N_3_PB_2013.pdf	_	_	_	_	_	_	_	SURFACE SHIP	662
35	0603271N_3_PB_2013.pdf	_	_	_	_	POWER MANAGEMENT	_	_	_	662
36	0603640M_3_PB_2013.pdf	_	_	_	_	POWER MANAGEMENT	_	_	_	662
37	0605863N_6_PB_2013.pdf	_	_	_	_	_	_	_	SURFACE SHIP	662
38	0602435N_2_PB_2013.pdf	_	_	_	WAVE OCEAN	_	_	_	_	662
39	0603747N_3_PB_2013.pdf	_	_	_	_	_	_	_	SURFACE SHIP	662

The match matrix for Theme 732 suggests that the PEs mentioned ("ship surface," "fleet surface," "power management," "ship power," "supplying power," and "generating power") might be good candidates to engage action plans mentioned ("mobile power," "electric warship," "training centers" and "ocean wave"). These PEs include, for example, the following:

- PE 0603563N: Ship Concept Advanced Design
- PE 0602123N: Force Protection Applied Res
- PE 0603573N: Advanced Surface Machinery Sys
- PE 0206624M: Marine Corps Cmbt Services Supt
- PE 0603114N: Power Projection Advanced Technology
- PE 0601153N: Defense Research Sciences
- PE 0602131M: Marine Corps Lndg Force Tech

Id	navy_2013(Online)	actions_10_0.73.txt	actions_11_0.76.txt	actions_17_1.08.txt	actions_18_0.71.txt	actions_20_1.14.txt	actions_25_0.88.txt	actions_36_0.50.txt	actions_5_0.56.txt	Total Row LLA Score
1	0603724N_4_PB_2013.pdf	_	SAVING ENERGY	_	_	_	SAVING FUEL	_	SAVING ENERGY	3861
2	0602235N_2_PB_2013.pdf	_	MEDIA SOCIAL	MEDIA SOCIAL	_	_	_	_	_	2574
3	0603640M_3_PB_2013.pdf	_	_	_	PROJECTION POWER;PLATFORMS MARINE	_	_	_	_	2574
4	0604231N_5_PB_2013.pdf	_	_	_	PROJECTION POWER	_	_	RESOURCES INFORMATION	_	2574
5	0205604N_7_PB_2013.pdf	_	_	_	_	PLATFORMS EXISTING	_	_	_	1287
6	0204229N_7_PB_2013.pdf	_	_	_	_	PLATFORMS EXISTING	_	_	_	1287
7	0603114N_3_PB_2013.pdf	_	_	_	PROJECTION POWER	_	_	_	_	1287
8	0601152N_1_PB_2013.pdf	_	_	_	PROJECTION POWER	_	_	_	_	1287
9	0604567N_5_PB_2013.pdf	_	_	_	PROJECTION POWER	_	_	_	_	1287
10	0605152N_6_PB_2013.pdf	_	_	_	PROJECTION POWER	_	_	_	_	1287
11	0602651M_2_PB_2013.pdf	_	_	_	PROJECTION POWER	_	_	_	_	1287
12	0602123N_2_PB_2013.pdf	_	_	_	PROJECTION POWER	_	_	_	_	1287
13	0206313M_7_PB_2013.pdf	PLATFORMS HARDWARE	_	_	_	_	_	_	_	1287
14	0602750N_2_PB_2013.pdf	_	_	_	PROJECTION POWER	_	_	_	_	1287
15	0603673N_3_PB_2013.pdf	_	_	_	PROJECTION POWER	_	_	_	_	1287
16	0602131M_2_PB_2013.pdf	_	_	_	PROJECTION POWER	_	_	_	_	1287
17	0603123N_3_PB_2013.pdf	_	_	_	PROJECTION POWER	_	_	_	_	1287
18	0603573N_4_PB_2013.pdf	_	_	_	_	PLATFORMS EXISTING	_	_	_	1287
19	0602114N_2_PB_2013.pdf	_	_	_	PROJECTION POWER	_	_	_	_	1287
20	0602236N_2_PB_2013.pdf	_	_	_	PROJECTION POWER	_	_	_	_	1287

The match matrix for Theme 449 suggests that the PE mentioned ("power projection") can be used to engage "social media" for "fuel/energy saving."

- Action 11: Enhanced education to develop an energy efficient fleet, engage major universities to create a cross-disciplinary curriculum for “energy design” in all fields for all forms of energy.

Id	navy_2013(Online)	actions_10_0.73.txt	actions_18_0.71.txt	actions_22_0.63.txt	actions_24_0.54.txt	actions_25_0.88.txt	actions_26_1.44.txt	actions_34_1.00.txt	actions_5_0.56.txt	actions_6_0.41.txt	Total Row LLA Score
1	0603724N_4_PB_2013.pdf		SUPPLY FUEL		SUPPLY FUEL	OPERATIONS SHIP	OPERATIONS FLEET SUPPLY FUEL				5490
2	0603570N_4_PB_2013.pdf	CONSTRUCTION SHIP					IRON BATH IRON WORKS			CONSTRUCTION SHIP	4392
3	0204202N_5_PB_2013.pdf	CONSTRUCTION SHIP					IRON BATH IRON WORKS			CONSTRUCTION SHIP	4392
4	0603721N_4_PB_2013.pdf	CONSTRUCTION SHIP					OPERATIONS FLEET		CONSTRUCTION MILITARY	CONSTRUCTION SHIP	4392
5	0603582N_4_PB_2013.pdf	CONSTRUCTION SHIP					KEEPING SEA			CONSTRUCTION SHIP	3294
6	0604777N_5_PB_2013.pdf	CONSTRUCTION SHIP								CONSTRUCTION SHIP	2196
7	0603512N_4_PB_2013.pdf	CONSTRUCTION SHIP								CONSTRUCTION SHIP	2196
8	0604567N_5_PB_2013.pdf	CONSTRUCTION SHIP								CONSTRUCTION SHIP	2196
9	0605853N_6_PB_2013.pdf					OPERATIONS SHIP		OPERATIONS RESEARCH			2196
10	0603564N_4_PB_2013.pdf	CONSTRUCTION SHIP								CONSTRUCTION SHIP	2196
11	0602123N_2_PB_2013.pdf	CONSTRUCTION SHIP								CONSTRUCTION SHIP	2196
12	0603563N_4_PB_2013.pdf	CONSTRUCTION SHIP								CONSTRUCTION SHIP	2196
13	0603725N_4_PB_2013.pdf			WORKS PUBLIC					CONSTRUCTION MILITARY		2196
14	0602235N_2_PB_2013.pdf							OPERATIONS RESEARCH			1098
15	0604262N_5_PB_2013.pdf						OPERATIONS FLEET				1098
16	0605152N_6_PB_2013.pdf					OPERATIONS SHIP					1098
17	0204571N_7_PB_2013.pdf						OPERATIONS FLEET				1098
18	0605879M_6_PB_2013.pdf							OPERATIONS RESEARCH			1098
19	0605154N_6_PB_2013.pdf						OPERATIONS FLEET				1098
20	0603236N_3_PB_2013.pdf							OPERATIONS RESEARCH			1098
21	0603739N_4_PB_2013.pdf								CONSTRUCTION MILITARY		1098
22	0205601N_7_PB_2013.pdf								CONSTRUCTION MILITARY		1098
23	0602435N_2_PB_2013.pdf						OPERATIONS FLEET				1098
24	0602236N_2_PB_2013.pdf							OPERATIONS RESEARCH			1098
25	0308601N_7_PB_2013.pdf							OPERATIONS RESEARCH			1098

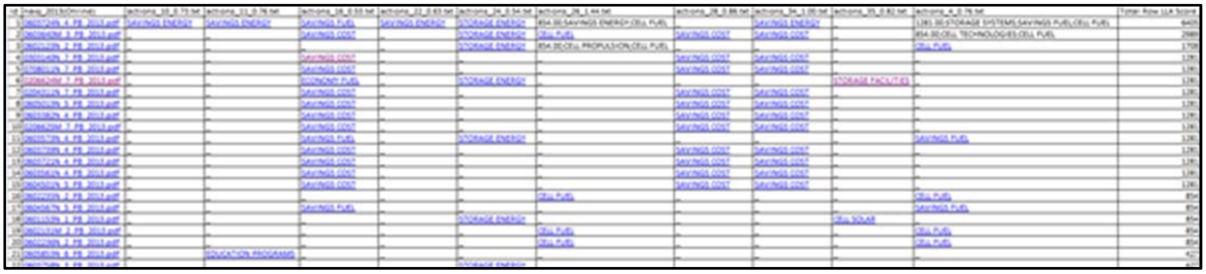
The match matrix for Theme 682 suggests that the PEs mentioned (“ship construction,” “ship operations,” “fleet operations,” “military construction,” and “operations research”) can be good candidates to engage Action Plans 10, 26, and 6.

- Action Plan 10: In this era of convergence, reduce the number of shipboard systems and focus more on small computers with high capability (Android, iOS apps).
- Action Plan 26: Expand the use of nuclear power in the fleet and ashore.
- Action Plan 6: Implement large umbrellas for ships to use shading to keep ship cooler; also use “carport” structures for ships docked on the pier.

Id	navy_2013(Online)	actions_16_0.53.txt	actions_18_0.71.txt	actions_27_0.88.txt	actions_28_0.86.txt	actions_34_1.00.txt	actions_35_0.82.txt	Total Row LLA Score
2	0205633N_7_PB_2013.pdf	PART LIFE	SPARE PARTS					2130
3	0205604N_7_PB_2013.pdf					COMMUNICATION DATA		1065
4	0604280N_5_PB_2013.pdf			PROGRAMMABLE RADIO				1065
5	0604307N_5_PB_2013.pdf	PARTS REPLACEMENT						1065
6	0206624M_7_PB_2013.pdf		COMMUNICATION EQUIPMENT					1065
7	0605853N_6_PB_2013.pdf			GUIDANCE SUPPORTING				1065
8	0603542N_4_PB_2013.pdf	PARTS REPLACEMENT						1065
9	0206313M_7_PB_2013.pdf					COMMUNICATION DATA		1065
10	0602750N_2_PB_2013.pdf						URBAN ENVIRONMENTS	1065
11	0604503N_5_PB_2013.pdf		COMMUNICATION EQUIPMENT					1065
12	0604404N_5_PB_2013.pdf				WING AIR			1065
13	0603271N_3_PB_2013.pdf	PARTS REPLACEMENT						1065
14	0604231N_5_PB_2013.pdf					COMMUNICATION DATA		1065

The match matrix for Theme 257 suggests that the PEs mentioned (“parts replacement,” “communication equipment,” “air wing,” “communication data,” and “urban environments”) might be good candidates for Action Plans 16, 18, 27, 28, 34, and 35.

- Action 16: Using synthetic lubricants to save 5% to 25% of energy costs.
- Action 18: Offshore basing.
- Action 27: Upgrade Navy housing with SMART grids to reduce energy consumption. By individualizing electricity/utility bills to single households, family users will be motivated to increase energy saving efforts.
- Action 28: Power on-board minor electronics with stationary bikes used for personnel fitness training.
- Action 34: Online feedback and social networking.
- Action 35: 3D farming: Less land use and local agriculture reducing fuel use and potential location of bio-fuel crops.



#	navy_2013(Ohrime)	actions_10_0.75.txt	actions_11_0.76.txt	actions_16_0.53.txt	actions_22_0.63.txt	actions_24_0.54.txt	actions_26_1.44.txt	actions_28_0.86.txt	actions_34_1.00.txt	actions_35_0.82.txt	actions_4_0.76.txt	Total Row LLA Score
1	[illegible]	SAVINGS ENERGY	SAVINGS ENERGY	SAVINGS FUEL	SAVINGS ENERGY	STORAGE ENERGY	854.00:SAVINGS ENERGY;CELL FUEL	–	SAVINGS ENERGY	–	1281.00:STORAGE SYSTEMS;SAVINGS FUEL;CELL FUEL	[illegible]
2	[illegible]	–	–	SAVINGS COST	–	STORAGE ENERGY	CELL FUEL	SAVINGS COST	SAVINGS COST	–	854.00:CELL TECHNOLOGIES;CELL FUEL	[illegible]
3	[illegible]	–	–	–	–	STORAGE ENERGY	854.00:CELL PROPULSION;CELL FUEL	–	–	–	CELL FUEL	1708
4	[illegible]	–	–	SAVINGS COST	–	–	–	SAVINGS COST	SAVINGS COST	–	–	1281
5	[illegible]	–	–	SAVINGS COST	–	–	–	SAVINGS COST	SAVINGS COST	–	–	1281
6	[illegible]	–	–	ECONOMY FUEL	–	STORAGE ENERGY	–	–	–	STORAGE FACILITIES	–	1281
7	[illegible]	–	–	SAVINGS COST	–	–	–	SAVINGS COST	SAVINGS COST	–	–	1281
8	[illegible]	–	–	SAVINGS COST	–	–	–	SAVINGS COST	SAVINGS COST	–	–	1281
9	[illegible]	–	–	SAVINGS COST	–	–	–	SAVINGS COST	SAVINGS COST	–	–	1281
10	[illegible]	–	–	SAVINGS COST	–	–	–	SAVINGS COST	SAVINGS COST	–	–	1281
11	[illegible]	–	–	SAVINGS FUEL	–	STORAGE ENERGY	–	–	–	–	SAVINGS FUEL	1281
12	[illegible]	–	–	SAVINGS COST	–	–	–	SAVINGS COST	SAVINGS COST	–	–	1281
13	[illegible]	–	–	SAVINGS COST	–	–	–	SAVINGS COST	SAVINGS COST	–	–	1281
14	[illegible]	–	–	SAVINGS COST	–	–	–	SAVINGS COST	SAVINGS COST	–	–	1281
15	[illegible]	–	–	SAVINGS COST	–	–	–	SAVINGS COST	SAVINGS COST	–	–	1281
16	[illegible]	–	–	–	–	–	CELL FUEL	–	–	–	CELL FUEL	854
17	[illegible]	–	–	SAVINGS FUEL	–	–	–	–	–	–	SAVINGS FUEL	854
18	[illegible]	–	–	–	–	STORAGE ENERGY	–	–	–	CELL SOLAR	–	854
19	[illegible]	–	–	–	–	–	CELL FUEL	–	–	–	CELL FUEL	854
20	[illegible]	–	–	–	–	–	CELL FUEL	–	–	–	CELL FUEL	854
21	[illegible]	–	EDUCATION PROGRAMS	–	–	–	–	–	–	–	–	427
22	[illegible]	–	–	–	–	STORAGE ENERGY	–	–	–	–	–	[illegible]

The match matrix for Theme 198 suggests that the PEs mentioned ("energy saving," "fuel savings," "cost savings," "fuel cell," "cell technologies," "storage energy," and "storage systems") might be good candidates to engage Action Plans related to these concepts.

The resulted matrices from this task will help design the specific questions to address the issues on a program-to-program basis to continue the energyMMOWGLI game with acquisition professionals in the acquisition research community in the future.

Addressing Counterfeit Parts in the DoD Supply Chain[1]

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Introduction

In June 2007, the U.S. Department of the Navy, Naval Air Systems Command (NAVAIR), asked the Bureau of Industry and Security's (BIS) Office of Technology Evaluation (OTE) to conduct a defense industrial base assessment of counterfeit electronics. NAVAIR suspected that an increasing number of counterfeit/defective electronics was infiltrating the DoD supply chain and affecting weapon system reliability. OTE data revealed that 39% of companies and organizations participating in the survey encountered counterfeit electronics during the four-year study period. Moreover, the

[1] This is a summary of the full report, which will be available in July 2013.

frequency of detected counterfeit incidents was escalating rapidly, rising from 3,868 incidents in 2005 to 9,356 incidents in 2008. These counterfeit incidents included multiple versions of DoD qualified parts and components (U.S. Department of Commerce, 2010).

Today, the DoD procures systems and products from a large network of global suppliers and manages over four million different parts at a cost of over $94 billion (GAO, 2010). As the DoD draws from this increasingly global supplier base, its visibility into these source companies is often limited; quality controls are, at times, insufficient; and chain of custody verification is lacking. As a result, the challenge of assuring the integrity and provenance of parts and components has grown geometrically more complex in this global sourcing environment.

When they are installed in systems, counterfeit parts and components can affect the safety, operational readiness, cost, and critical nature of the military mission. Almost any part can be counterfeited—including fasteners used on aircraft, electronics used on missile guidance systems, and materials used in body armor and engine mounts. Counterfeit parts have the potential to cause a serious disruption to DoD supply chains, delay ongoing missions, and even affect the integrity of weapons systems (GAO, 2010).

Additionally, as DoD weapon systems age, products required to support them may no longer be available from the original manufacturers or through franchised or authorized suppliers. Instead, the DoD must turn to independent distributors, brokers, or aftermarket manufacturers as sources of supply. Here again, the DoD is at risk for acquiring counterfeit parts.

At the same time, counterfeiters continue to develop more sophisticated capabilities, making detection all the more difficult. For instance, third-party subcontractors for major defense companies have been found to manufacture working components, only to mix them with cheaper parts of inferior quality and/or non-working components. Needless to say, schemes of this sort make determining the provenance of counterfeit components exceedingly difficult.

Over the years, counterfeiters have also fine-tuned their ability to replicate parts, often by relying on scrap materials that were thought to have been destroyed (Martin, 2012). The burgeoning practice of harvesting and, often, repurposing electronic waste or “e-waste” (e.g., discarded computers, office electronic equipment, entertainment device electronics, mobile phones, telephones, and refrigerators) poses a growing challenge to the DoD. In the slums of China, India, and Pakistan, peasants “cook” circuit boards over trash can fires in order to remove the metal chips, selling them to local counterfeiting operations. Once the chips are cleaned, refurbished, and relabeled, they are purchased by unscrupulous military subcontractors that go on to supply “military grade” microchips to many of America’s largest defense companies. According to a 2012 GAO report, some of these microchips are then used in some of the DoD’s major weapons systems.

In this environment, the DoD must step up its war against counterfeit parts, much as private industry has done. For example, counterfeit drugs are rare (at least in the United States) thanks to the relatively high level of safety assuredness for U.S. pharmaceuticals (Lechleiter, 2012). This includes the review of production yields, capacity, and/or product amounts compared with raw material purchases. Given the relative ease with which authentic-looking drugs can be reproduced (indeed, reproducing packaging is more expensive than making the fake drug), it is remarkable that there are so few reported instances of counterfeits.

Across the DoD supply chain, however, counterfeits of all types—from electronic equipment to metal fasteners—have been found. As a direct consequence, the lives of military men and women are at stake. Thus far, the impact of counterfeit parts has been minimal in this regard. According to Pentagon Press Secretary, George Little, “[the DoD] is unaware to date of any loss of life or catastrophic mission failure that has occurred because of counterfeit parts” (Garamone, 2012, p. 1). But given the growth of the availability of counterfeit parts, it may only be a matter of time.

All branches of the Services are affected by the threat of counterfeit parts. The following examples illustrate cases in which counterfeit parts have infiltrated the Services’ supply chains (GAO, 2010).

- **Army: Seatbelt clasps.** Seatbelt parts were made from a grade of aluminum that was inferior to that specified in the DoD’s requirements. The parts were found to be deficient when the seatbelts were accidentally dropped and they broke.
- **Navy: Routers.** The Navy, as well as other DoD and government agencies, purchased counterfeit network components—including routers—that had high failure rates and the potential to shut down entire networks. A two-year FBI criminal investigation led to 10 convictions and $1.7 million in restitution.
- **Air Force: Microprocessor.** The Air Force needed microprocessors that were no longer produced by the original manufacturer for its F-15 flight-control computer. These microprocessors were procured from a broker, and F-15 technicians noticed additional markings on the microprocessor and character spacing inconsistent with the original part. A total of four counterfeit microprocessors were found and as a result were not installed on the F-15’s operational flight control computers.
- **Defense Logistics Agency: Packaging and small parts.** During a two-year period, a supplier and three co-conspirators packaged hundreds of commercial items from hardware and consumer electronics stores and labeled them as military-grade items. For example, a supplier labeled the package containing a circuit from a personal computer as a $7,000 circuit for a missile guidance system. The suppliers avoided detection by labeling packages to appear authentic, even though they contained the wrong part. The supplier received $3 million from contracts totaling $8 million before fleeing the country.

Defense contractors are encouraged to report counterfeits using the Government Industry Data Exchange Program (GIDEP) database. GIDEP serves as a data repository for the collection and sharing information on nonconforming parts and materials, including information on suspect counterfeit products, allowing government and industry participants to share information. However, not all participants are willing to share such information. This is not surprising given the lack of clear incentives, especially if the participating firm believes their reputation may be damaged as a result.

In order to reduce the risk of counterfeit parts in the DoD supply chain, we provide the following high-level recommendations:

- Partner with industry to develop a network of trusted providers.
- Mandate that suppliers report suspect counterfeits using GIDEP and provide penalties for non-compliance.

- Require that the supplier absorb any costs associated with the removal and replacement of counterfeit parts or components that make their way into DoD systems.
- Invest in visibility systems to track the provenance and transport of parts and components.
- Adopt regionalized supply chains to reduce supplier and transport risk.

The threat of counterfeit parts within the DoD's supply chain is real and will only escalate over time, with potentially serious consequences. In order to reduce this threat, the DoD and its industry partners will have to work together. While both may have the best intentions, it is essential that incentives, penalties, and rewards are properly aligned in order to produce the desired outcome.

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Wave Release Strategies to Improve Service in Order Fulfillment Systems[1]

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Abstract

Using the Defense Logistics Agency's current service performance metric Next Scheduled Departure, we develop methodologies for establishing the optimal timing of order releases in a distribution center so that customers receive supplies sooner. We present a simulation model to test these methodologies and to show that setting wave release times accordingly can significantly improve service performance for systems subject to stationary and non-stationary arrivals.

Introduction

Continuing fiscal struggles in the federal government have made "do more with less" the operating mode of almost every Department of Defense (DoD) organization. The Defense Logistics Agency (DLA) and its distribution centers are no exception. In DLA's case, there is increasing pressure to provide superior service with the same or fewer labor resources. By "superior service," we mean rapid response to customer requisitions.

"Operational availability" (A_o) of a system is defined as the fraction of time or probability that a system's capabilities will be available for operational use ("Operational Availability Handbook," 2003). A_o is a function of "uptime" and "downtime," the latter being mainly determined by Mean Logistics Delay Time (MLDT). Intuitively, reducing the flow time—the time between arrival of the order and the time it is ready to ship—decreases MLDT and therefore improves A_o. In general, the more quickly the logistics system responds to the requests, the higher the availability of end items because total downtime is reduced through reduced MLDT.

If a part is in stock, logistics delay time is comprised of two main components: warehouse processing time and transportation time. These two processes (warehousing and transportation) meet at the shipping dock. Doerr and Gue (2011) observed that warehouse operations are effectively "continuous," in that completed orders arrive at a shipping dock, more or less, in a continuous stream. By contrast, transportation is a cyclical process, due to the need to achieve economies of scale. Thus, for example, package carriers such as UPS and FedEx have a "nightly sort" and "next day" deliveries. Less-than-truckload (LTL) carriers, which transport larger shipments, also operate according to a daily, cyclical model.

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To coordinate the internal, continuous operations of its DCs with the cyclical transportation schedules of its transportation providers, DLA uses a metric called Next Scheduled Departure (NSD), which measures the fraction of orders arriving during a specified 24-hour period that are processed before a specific truck departure (Doerr & Gue, 2011). By definition, an increase in the metric means more orders make their last departing trucks, and that some customers receive their orders before they otherwise would have. For repair parts and mission-critical consumables, therefore, increasing NSD reduces MLDT and increases operational readiness.

One would think that making an order available to pickers as soon as it arrives would increase its chance of making it onto the next departing truck, but such a view misses the economies of scale in a picking operation. A worker picking a large batch is much more efficient than a worker picking a single order, and therefore his capacity is higher. Higher capacity reduces waiting for arriving orders, and therefore tends toward lower total sojourn times. The benefits of large batches, however, must be weighed against the queueing time necessary to form the batch. To strike this balance, DCs at DLA release orders in large batches called waves.

Despite the ubiquity of wave operations in commercial (and military) warehouses, there are no analytical models to determine the optimal number and timing of these waves, especially to maximize performance against deadline-oriented metrics such as NSD, which is used at DLA. (A thorough review of literature is given in Çeven and Gue, 2013.) The goal of our work is to improve the service performance and thus MLDT of a distribution center (operated by DLA, the Services, or a third party) by properly setting wave release times.

In the next section, we discuss fulfillment operations at DLA Distribution Center, Susquehanna, PA, a fulfillment center operated by DLA Distribution. We analyze its order flow data and the current wave release strategy. In the section Optimal Wave Release Policies, we introduce our approximation models and use those models to verify a simulation model. We discuss the details of the simulation model in the Simulation Study section and summarize our findings in our conclusion.

Wave Operations at DLA Distribution

DLA Distribution Susquehanna, Pennsylvania (hereafter, DDSP) is an extremely complex distribution operation handling more than one million stock-keeping units (SKUs) stored among dozens of warehouses. One of its main service offerings is Dedicated Truck, in which a customer requests specific times of delivery each day or week. Delivery times could be, for example, daily at 1600, or every Tuesday and Friday at 1200, depending on the customer. DDSP then establishes departure times for trucks leaving to each Dedicated Truck customer.

Because an order arriving just before truck departure cannot possibly be processed in time, DDSP establishes an internal cutoff time (or set of cutoff times, as appropriate) for each Dedicated Truck customer. Orders arriving before that time are due on the appropriate “next truck” and must be processed before it departs. Distribution centers in the DLA measure their service performance with NSD, which measures the percentage of orders arriving between consecutive cutoff times that make it on the assigned truck. Figure 1 illustrates how the metric works.

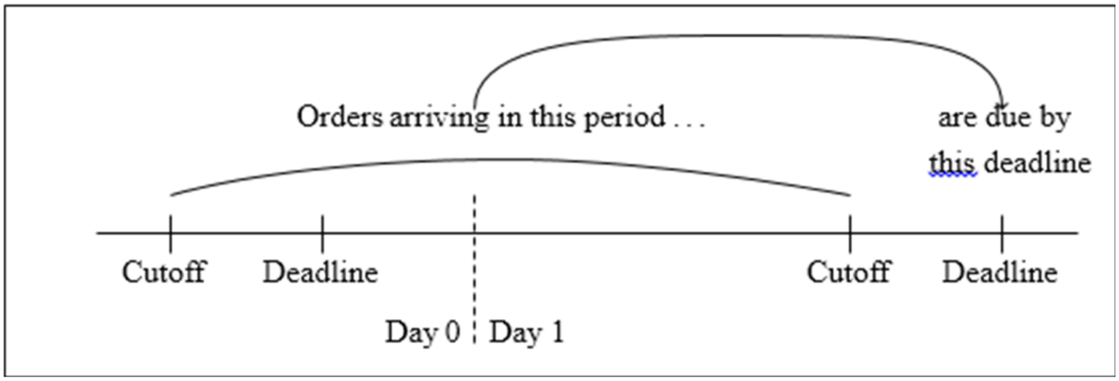

Figure 1. Orders Arriving Between Consecutive Cutoff Times Are Due on the Next Deadline

Managing the release of work to the system in such an environment is a difficult task, to say the least, and especially so in the presence of waves. In a typical distribution operation, including at DDSP, there are 2–6 waves per day, depending on the workload and number of destinations that must be served. Figure 2b shows the scheduled wave release times at DDSP at the time of our study—0000, 0400, 0930, and 1600. In addition to these scheduled releases, orders were occasionally released manually at around 0700 and 0900 to balance the workload.

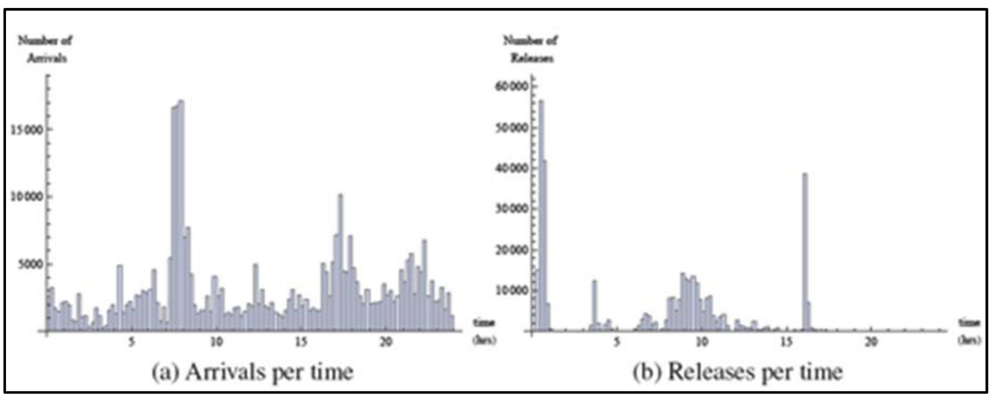

Figure 2. Number of Orders Arrived and Released Within a Day

It is our experience that the number and timing of order releases is based on intuition and experience of management. Could NSD be improved if the release times were changed? What level of benefit is possible? Before looking at the details of DDSP, we present an overview of mathematical models to establish order release times.

Optimal Wave Release Policies

We first discuss some major results from Çeven and Gue (2013), in which the arrival process is assumed to be stationary with rate λ orders per unit time. The authors propose a fluid approximation model in which individual orders are indistinguishable. (They also specify in which conditions this approximation is valid.) To maintain stability, the server's capacity is assumed to be $\mu > \lambda$.

Arriving orders accumulate in a Warehouse Management System (WMS) virtual queue until the next wave is released, at which time the quantity of orders in that wave decreases at rate μ until the wave is complete. Waves in this model are not allowed to overlap; that is, the current wave must be complete before a new wave can begin. While the server is working a wave, orders in the next wave accumulate, and the cycle continues. The

cutoff time for accepting orders is assumed to be equal to the truck departure time, which is a worst case in terms of NSD. This assumption is not necessary, but it makes the presentation much easier. Çeven and Gue (2013) discuss how to assign a realistic cutoff time.

NSD in a single-wave system is a function of the wave release time w_1, the arrival rate λ, and the server capacity μ. By definition,

$$\mathrm{NSD} = \frac{\text{\# orders worked today that arrived today}}{\text{\# orders that arrived today}} \tag{1}$$

When there is a single class of orders (which is a simplest version of DDSP's original problem), the server should finish the wave exactly at the deadline, and therefore $w_1 = 1 - \rho$. Thus, the optimal NSD for a single wave system is $w_1^* = \mathrm{NSD}^* = 1 - \rho$. This proposition alone provides important insights. First, the server should begin the work as late as possible in order to allow as many orders as possible to make it into the wave. Second, the wave should finish exactly at the deadline. Furthermore, the result suggests that the optimal cutoff time equals the optimal wave release time $w_1 = 1 - \rho$, for which NSD would be 100%. This can also be argued intuitively: releasing the wave before the cutoff time means some orders arrive after the release but before the cutoff. These orders will certainly miss the truck. Releasing the wave after the cutoff time means some orders are in the wave but are not due on the next truck, which reduces system capacity for the orders that need to be processed immediately. Neither condition should be optimal, as the result shows mathematically. Çeven and Gue (2013) also address the multiple wave systems and determine the closed form optimal wave release times for a system with stationary arrivals:

$$\mathrm{w_j} = \begin{cases} \frac{j-1}{N} & , \text{for } \lambda = \mu \\ 1 - \frac{\rho^j - \rho^{N+1}}{1-\rho^{\,N}} & , \text{for } \lambda < \mu. \end{cases} \tag{2}$$

The authors observe that the first release time does not change, but later wave times adjust as the number of waves increases. As expected $w_N = 1 - \rho$ when $N = 1$, and w_N (and NSD) converges to 1 as the number of waves $N \to \infty$. That is, NSD improves as more waves are released, especially when expected utilization is high. As utilization increases, the equation suggests that the maximum possible NSD decreases, converging to $(N - 1)/N$. The models presented in Çeven and Gue (2013) can also be extended to reflect uncertainty in both daily workload and capacity uncertainty as well as daily non-stationary arrivals. Although their results provide insight into the importance of setting proper wave release times, they only partially address the problem faced by DDSP. This is because Dedicated Truck operations are only a portion of each day's workload at DDSP, so it is impossible to assess capacity devoted to these orders. Another reason is the fact that DDSP often receives orders days in advance of when they are scheduled to ship, and many orders remain in queue until near their deadline. Another complication that is not addressed by Çeven and Gue (2013) is the existence of multiple deadlines. Nevertheless, the results in Çeven and Gue (2013) provide us with the ability to simulate and test different wave release policies.

Simulation Study

Using a data set from DDSP, we analyzed the existing order arrival stream and wave release policy in order to generate input for the analytical models. Distribution centers of DLA typically have outbound processes that include picking, packing, order consolidation, and shipping. Example flow timing data is given in Table 1.

Table 1. Order Flow Timing Data Sample

OD ORD	SD DT	SD TI	MIT DT	MIT TI	LS DT	LS TI	ICK DT	ICK TI	ACK DT	ACK TI	FFER DT	FFER TI	ISSION DT M	ISSION TI N
8002R005	010061	35900	010060	21206	010060	22633	010060	35404	010060	53610	010060	61740	010060 2	01700 2
8002R007	010061	35900	010060	21207	010060	22633	010060	35052	010060	53737	010060	61740	010060 2	01700 2

The first entry in Table 1 refers to the order ID. All date and time fields are defined as Julian day and military time, respectively (e.g., 2010257 refers to September 17, 2010; 230140 refers to time 2301 and 40 seconds). The following two fields refer to the scheduled departure time followed by the arrival date and time of the order. The field RLS refers to the date and time that the order is released for picking. Pick completion date and time is given in PICK DT and PICK TI. The completion date and time of packing is given in fields PACK DT and PACK TI. Because orders wait for consolidation, there is a consolidation date and time stamp (given with OFFER DT and OFFER TI). The last two data fields correspond to the actual shipment date and time. Figure 3 is an illustration of order flow.

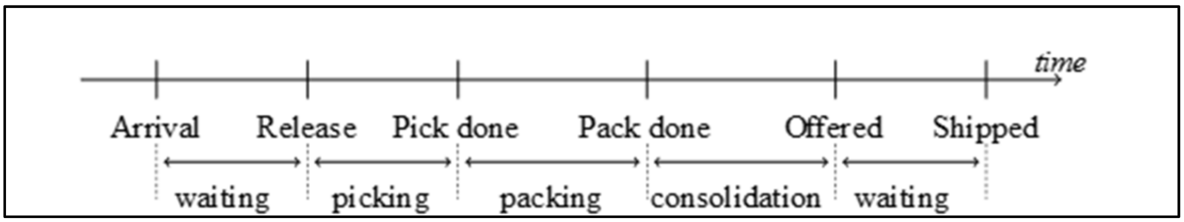

Figure 3. Timeline of an Order Through Arrival-to-Ship Process

We were provided with three months of order flow data from January 2010 to March 2010 for Dedicated Truck operations (DTK)—a total of 402,406 orders. Of those orders, 351,866 arrived in 2010 (87.44% of total) and 351,530 (87.36% of total) orders were shipped during the three-month interval and were the subject of our analysis.

The managers of DDSP reported that the overall system performance in NSD was around 72% over the three-month period (75.0% in January, 57.9% in February, and 70.4% in March 2011). We observe that NSD is highly variable throughout the length of study, within a range of [22.7%, 100%]. On average, 72% of the customer orders were fulfilled by their deadline; however, on some days NSD dropped below 60% (see Figure 4).

Before describing the simulation, we must cover one last detail. Figure 2 shows that the arrival stream to DDSP is highly non-stationary. Çeven and Gue (2013) show how to modify the basic wave release model to handle this case. The “discretized” version of their model assumes the arrival rate in a discrete period of time (in this case, 15 minutes) is stationary, but that the mean rate may change from hour to hour.

Below we discuss both intuitive and optimal wave release policies and show how proper release times can improve NSD. The simulation study serves two purposes: (1) to verify the analytical models of Çeven and Gue (2013), and (2) to demonstrate that service performance can be improved with proper wave release times.

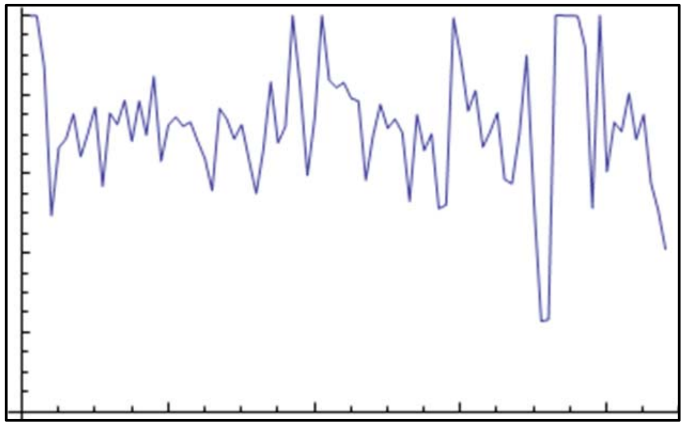

Figure 4. Recorded Daily NSD and DDSP

We model the order fulfillment system as a three-stage queuing system corresponding to the picking, packing, and shipping processes. We assume 20 servers per stage and identical exponential processing time distributions in each stage. This choice is arbitrary, of course, but in the absence of real data (DLA does not collect processing time data), we had no justification for another choice. Arriving orders are stored in a virtual queue and released in the next wave. Once an order is released for picking, available workers start picking orders. Completed orders are sent directly to packing and then to shipping. Because daily workload at DDSP varies, we test different levels of utilization ρ = 0.5, 0.75, 0.95. We adjust the (exponential) processing rate to maintain the appropriate utilization. We assume four waves per day, as in the operations at DDSP at the time of the study.

Before applying different wave release policies, we verify the simulation model by comparing simulated NSD with NSD according to the analytical models. Using a stationary arrival stream, we determine the optimal release times for a single class, four-wave system for each utilization level. Optimal release times suggest NSD would be 96.7%, 88.6%, and 78.1% for ρ = 0.5, 0.75, 0.95. We insert the release times into the SIMIO simulation software and run the model for 30 simulated days, with three days of warmup and 100 replications. Figure 5 shows the results. The analytical model approximates the corresponding system's NSD within 1%.

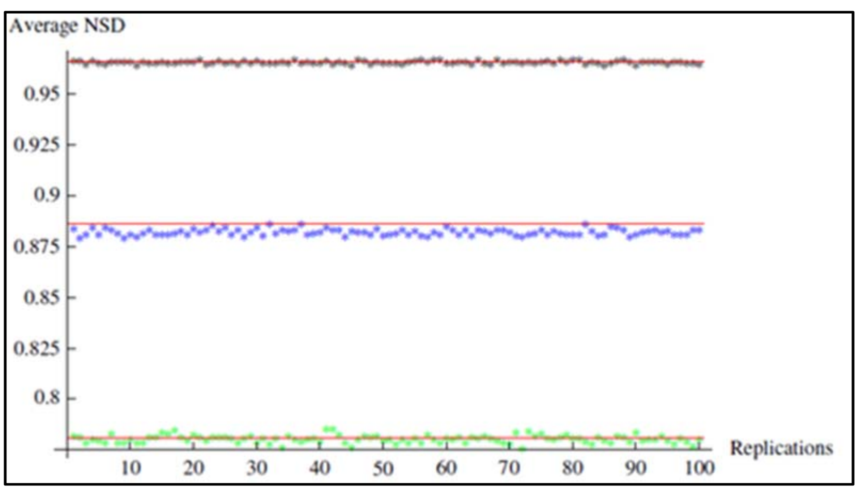

Figure 5. Verification of the Simulation Model

Note. The red line indicates the approximated NSD by the analytical model. Black, blue, and green data points correspond to the average simulated NSD for ρ = 0.5, 0.75, 0.95, respectively.

Consistent with the results in Çeven and Gue (2013), average NSD drops as utilization of the system increases. We also observe that the variability in NSD for both policies increases as ρ increases.

Next, we consider a non-stationary arrival stream representative of the DDSP data, but we scale the arrival rates to achieve an appropriate utilization. We first test an intuitive policy in which each wave has the same wave length. Because the system will be busy $\rho = 1 - w_1$ of the time, an equal time policy divides this interval into four equal waves.

To test the analytical model, we use the same non-stationary arrival data and determine optimal release times and NSD^*. We insert the optimal release times into the simulation model and estimate the NSD_e. Table 2 shows the release times for the optimal and equal time policies.

Table 2 shows the approximated NSD^* of the analytical model. Similar to our results for stationary arrivals, the simulation results are close to the approximations (e.g., the approximation overestimates the NSD by around 3%). The optimal policy performs 9.6%, 5.9%, and 1.2% better than the intuitive equal time policy for different levels of utilization. Recall that the model suggested more evenly distributed releases as utilization increases. We observe this situation especially for ρ = 0.95.

Table 2. Simulation Results for Non-Stationary Arrivals

$\rho = 0.5$	w_1	w_2	w_3	w_4	NSD^* (%)	NSD_e(%)
Optimal policy	12:00	18:05	21:18	22:53	96.4	93.3
Equal time policy	12:00	15:00	18:00	21:00	-	83.7
$\rho = 0.75$	w_1	w_2	w_3	w_4	NSD^* (%)	NSD_e(%)
Optimal policy	06:00	12:36	17:45	21:18	87.3	85.2
Equal time policy	06:00	10:30	15:00	19:30	-	79.3
$\rho = 0.95$	w_1	w_2	w_3	w_4	NSD^* (%)	NSD_e(%)
Optimal policy	01:12	07:30	12:47	18:24	78.3	75.9
Equal time policy	01:12	06:54	12:36	18:18	-	74.7

Conclusions

In this study, we have addressed order release problems in order fulfillment systems and shown that setting wave release times properly can improve NSD, and thus the operational availability of supported end items. In order fulfillment systems such as those operated by DLA, order releases should be timed to accommodate daily deadlines.

In a simulation study, we verified the analytical results in Çeven and Gue (2013) with both stationary and non-stationary arrival streams. We implemented those models to test optimal policies against an intuitive policy and showed that releasing waves optimally improves NSD. Although the complexity of operations at DDSP made direct analysis prohibitive, our results suggest that NSD could be improved with further investigation into the number and timing of order releases.

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Issues and Challenges in Self-Sustaining Response Supply Chains

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Abstract

The most basic representation of a supply chain has three elements: supply, demand, and the flow between the two. A humanitarian response supply chain (RSC) has to a large extent unknown demand and at best uncertain supply demand with disruptive flow. A self-sustaining supply chain (SSSC) requires that the supply chain itself provide all resources consumed while transporting supplies, thus complicating the operations with numerous challenges and unfamiliar issues. If an RSC is self-sustaining, it will reduce some of the uncertainties in supply. However, self-sustaining response supply chains (SSRSC) generate significant

additional cost for being extreme supply chains. To understand the costs associated with SSRSC observed in special operations and humanitarian assistance and disaster relief (HADR), they must be compared and contrasted against the known characteristics of traditional supply chains. This work explores the issues and challenges of SSRSC that arise in logistics networks.

Summary

We can partition supply chains into three broad categories in terms of how the supply chain manages material—traditional, sustainable, and self-sustainable. Traditional supply chains that function in traditional logistics networks have been well studied in operations management. Sustainable supply chains (SSC) have received considerable attention in this age of green consciousness and fiscal austerity, and they can be measured by looking at their agility, adaptability, and alignment (Lee, 2004). SSC often achieve these through "The Three R's": reduction, reuse, and recycling—the latter two "R's" are often performed outside of the traditional supply chain. Self-sustaining supply chains (SSSCs) extend themselves beyond the reuse and recycling. They require that all resources consumed while transporting supplies to their destinations be provided via the network itself. This makes SSSCs even more complex—they essentially become supply chain islands, where the network must be

- nimble enough to transport, create, conserve, and consume supply;
- flexible enough to repair and reuse the waste that it produces; and
- rigid enough to fulfill the ultimate demand of the supply chain while simultaneously fulfilling its own needs during the process of delivering the good or service it promises.

In addition to the management of material, one important aspect of supply chains is the environment in which they operate. At one end of the spectrum are traditional supply chains with less variable fluctuations in demand; on the other end are "response" supply chains in which supply, demand, customers, and network configurations continuously change due to unpredictability. A supply chain in its most basic form encompasses three elements: supply, demand, and flow—flow being the intermediary between the other two components. Typically, a traditional supply chain supplies a pre-established, standardized product to customers to meet a relatively constant and forecasted demand through structured resources and continuous flow. In contrast, at any given time, a humanitarian response supply chain supplies a wide range of products and services fulfilling spurts of demand while sharing the flow and capacity with other relief items (Apte, 2009). Traditional supply chain models may fail when they are stressed due to unknowns and uncertainties. Supply chains stressed in this way—extreme supply chains—need special attention from the researchers.

Sustainable, self-sustainable, and response supply chains are becoming more relevant to the Department of Defense (DoD) as we proceed through the 21st century. A major reason for this is the era of fiscal austerity that we have entered after the 2008 financial crisis. The U.S. DoD budget is tighter, so it must be able to maintain the same capabilities as in the past while using fewer resources. Thus, sustainability and self-sustainability become key strategic initiatives for the DoD. Strategy also comes into play when developing response supply chains—as people move to more disaster-prone areas of the world, the U.S. military will continue to play a major role in being the first responders in humanitarian assistance and disaster relief (HADR). Also, the face of conflict has tacked

towards more irregular enemies vice large armed forces, thus requiring smaller, independent teams that coexist with each other over long periods of time.

Virtually every supply chain, regardless of whether it is self-sustaining or not, shares common characteristics such as supply, inventory, distribution networks, flows, lead times, information systems, customers, demands, and key performance indicators. In this research we study the similarities and differences of SSRSC with SSSC to expose the challenges in SSRSC in terms of operations. We believe studying operations is the first step to understanding the burden of cost in such supply chains (Regnier & Nussbaum 2011a, 2011b).

When a self-sustaining supply chain is initiated, it is endowed with a certain set of goods. These goods are used to sustain the SSSC itself during the transport, and these may also be the same types of items that it is attempting to deliver to its customers. When a self-sustaining supply chain begins, it has a limited amount of space to carry all of the goods being delivered and consumed during the delivery. Therefore, the choice of goods to carry is critical in that the SSSC cannot restock during the delivery process. The carriers must be efficient, innovative, and sustainable in their use of goods—they must have the tools to not only reach their destination, but also to have the provisions that the customer desires. If the supply chain runs out of goods, not only does the customer not receive goods, but also the supply chain itself could perish, resulting in, at best, unfulfilled demand—at worst, loss of life. Thus, efficient reuse is critical, as space is at a premium. Furthermore, the logistics network in an SSSC could be unstable and variable over time. These SSSCs, especially within the context of HADR and DoD special operations, provide for a unique research opportunity that has not been thoroughly studied (see Figure 1).

For example, consider the supply chain of providing fuel. Transportation of this single commodity requires fuel to be consumed by vehicles that transport it. There exist numerous challenges in this network if it is to be self-sustaining. It has also been researched and proved that such SSSCs can incur significantly higher costs than traditional networks (Regnier, Simon, & Nussbaum, 2012). We in this project will study such challenges in response supply chains, where multiple goods are conveyed and consumed through the same network—a network that is rife with uncertainty.

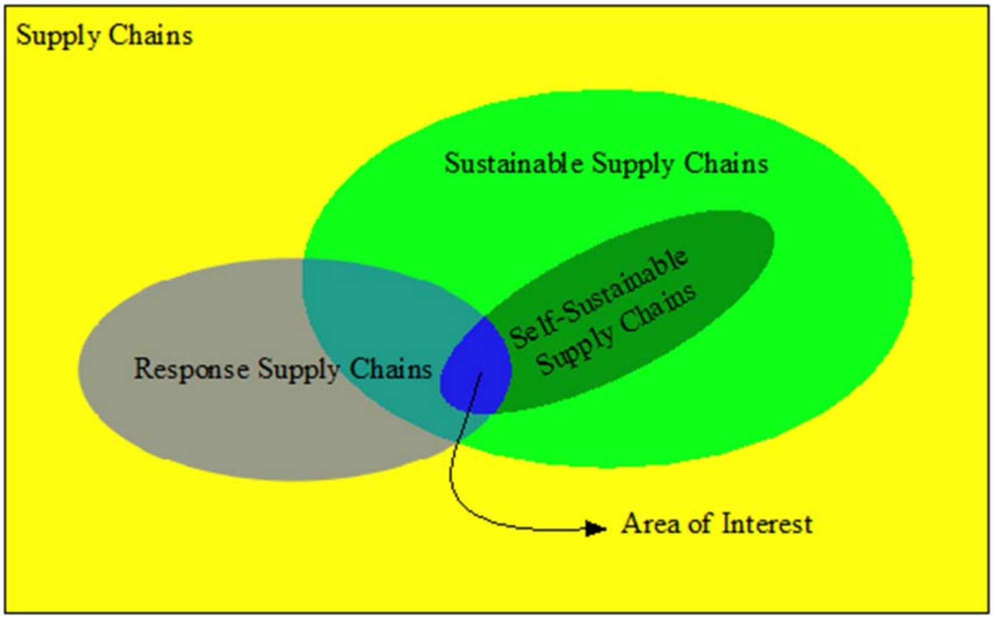

Figure 1. Positioning Self-Sustaining Response Supply Chains

Uncertainty in response supply chains is typified by "unknown unknowns," to quote Donald Rumsfeld. When disaster strikes, authorities do not know who is hurt, what the severity of the damage is, what portions of the network remain or are degraded, how the supply chain will develop in the future, where demand will materialize, where supply will materialize—to name a few unknowns. The only knowns are the goals to save lives and to reduce suffering. Saving lives involves delivering the goods that are needed to sustain life—the same goods, such as water, fuel, medical supplies, equipment, and information, that SSSCs use and deliver during their life cycles. In such instances, the transportation capabilities needed to deliver goods, save lives, and reduce suffering have to be reliable. The uncertainties are brought on due to the process of providing relief that in turn makes SSRSC more complex. We plan to explore these complexities in SSRSC, thus allowing the DoD to identify the burden of cost.

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Lead Time Demand Modeling in Continuous Review Supply Chain Models

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Abstract

This paper introduces a mixture distribution approach to modeling the probability density function for lead time demand (LTD) in problems where a continuous review inventory system is implemented. The method differs from the typical “moment-matching” approach by focusing on building up an accurate, closed-form approximation to the LTD distribution from its components by using mixtures of truncated exponential (MTE) functions. First, construction of the LTD is illustrated and the approach is compared to two other possible LTDs. This distribution is then utilized to determine optimal order policies in cases where a buyer makes its decisions alone, and later in a situation where members of a two-level supply chain coordinate their actions.

Introduction

Numerous probability models have been suggested for representing uncertain demand during lead time (LT) in continuous-review inventory management systems when both LT and demand per unit time (DPUT) are variable. A common approach to finding a distribution for lead time demand (LTD) involves modeling LT and DPUT with standard probability density functions (PDFs). Based on the distributions assigned, a compound probability distribution is determined for demand during lead time, or LTD. The latter distribution is used to determine reorder point and safety stock policies, and may be used to estimate inventory costs. In some cases, analytical formulas for optimal reorder point, safety stock, or stockout costs are available in terms of the compound distribution’s parameters, while in other situations the values associated with certain percentiles of the compound LTD distribution are estimated to provide these values. Although the problem of finding an appropriate LTD distribution has been well studied, papers written in recent years have continued to pursue methods that overcome unrealistic distributional assumptions (Ruiz-Torres & Mahmoodi, 2010; Vernimmen, Dullaert, Willimé, & Witlox, 2008).

This paper illustrates an approach for constructing a mixture distribution for LTD that allows the LT and DPUT distributions to be state-dependent. This method also allows input distributions that take any standard or empirical form. Use of the mixture distribution technique is first demonstrated in the context described by Cobb (2013), which is a single-item continuous-review inventory model for one buyer. For single-firm operating in a continuous-review inventory system, the mixture distribution method for modeling the LTD distribution differs from the typical “moment-matching” approach. The method focuses on

building up an accurate, closed-form approximation to the LTD distribution from its components by using mixtures of truncated exponential (MTE) functions.

After the mixture distribution approach is described, a two-level supply chain model where the buyer operates under uncertain demand and utilizes a continuous review inventory system will be considered. In this two-echelon supply chain model, credit terms (Chaharsooghi & Heydari, 2010), quantity discounts (Li & Liu, 2006; Chaharsooghi, Heydari, & Kamalabadi, 2011), and rebates (Cobb & Johnson, 2013) have been suggested as coordinating incentives that allow the supply chain members to divide the cost savings resulting from coordinating their order quantity and reorder point decisions. In each of these cases, LTD is assumed to be normally distributed. This assumption is not always realistic, particularly when DPUT and LT are each random variables such that LTD has a compound probability distribution (Eppen & Martin, 1988; Lau & Lau, 2003; Lin, 2008). This paper will incorporate the previously described model (Cobb, 2013) into the two-echelon supply chain problem to show that this model can obviate the need to assume that demand for the entire LT period is normally distributed.

The next section describes LTD distributions and uses an example dataset to show how standard PDFs can be used as approximations to the LTD distribution. The mixture distribution method is also used for the example problem. Next, the different approximations to the LTD distribution are used to find optimal inventory order quantity and reorder point policies. This is followed by an illustration of how the mixture distribution approach can allow more complicated LTD distributions to be incorporated into such problems. The two-level supply chain model is then introduced, and the mixture distribution approach is used to model LTD in the context of decentralized, centralized, and coordinated supply chains. The final section concludes the paper.

Lead Time Demand Distributions

LTD in a continuous-review inventory system is often assumed to follow a compound probability distribution. Suppose *L* is a random variable for lead time (LT) and *D* represents random demand per unit of time (DPUT). LTD is a random variable *X* determined as

$$X = D_1 + D_2 + \cdots + D_i + \cdots + D_L \ . \tag{1}$$

Therefore, *X* is a sum of random, independent, and identically distributed (i.i.d.) instances of demand. The mean and variance of *X* can be calculated as

$$E(X) = E(L) \cdot E(D) \text{ and } Var(X) = E(L) \cdot Var(D) + [E(D)]^2 \cdot Var(L). \tag{2}$$

Suppose the data in Table 1 is available to estimate an LTD distribution. This table contains 50 observations of daily demand for an inventory item and 10 observations for LT on orders of the same item. The expected value of daily demand is *E*(*D*)=2.88, and the variance of this random variable is *Var*(*D*)=2.84. LT has an expected value and variance of *E*(*L*)=5.3 and *Var*(*L*)=6.9, respectively. According to the formulas in Equation 2, the expected value and variance of LTD are *E*(*X*)=15.26 and *Var*(*X*)=72.3, respectively.

The remainder of this section will illustrate three possible methods for approximating the LTD distribution underlying the data in Table 1.

Normal Approximation

The service level is defined as the percentage of replenishment order cycles where demand during LT is satisfied. To determine the reorder point (*R*) required to achieve a desired service level, a typical textbook approach is to assume the LTD distribution is normal and use normal distribution tables or Excel formulas. For example, to find the *R* needed to achieve a 95% service level for the LTD distribution with expected value and

variance described in Table 1, the Excel formula NORM.INV(0.95,15.26,72.3^0.5) can be used to find R = 29.25.

Table 1. Observations for Daily Demand and Lead Time

Daily demand (DPUT)	1	2	2	1	4	1	1	1	1	1
	3	5	3	2	5	4	2	2	3	2
	2	3	3	3	1	3	6	3	6	2
	5	1	5	3	2	6	1	2	4	1
	3	2	2	2	6	5	5	1	3	7
Lead time (LT)	3	5	3	4	4	5	5	10	5	10

The normal approximation to the LTD distribution and the reorder point R=29.25 are illustrated graphically in Figure 1. By implementing this policy, we would expect to stockout on 5% of replenishment order cycles.

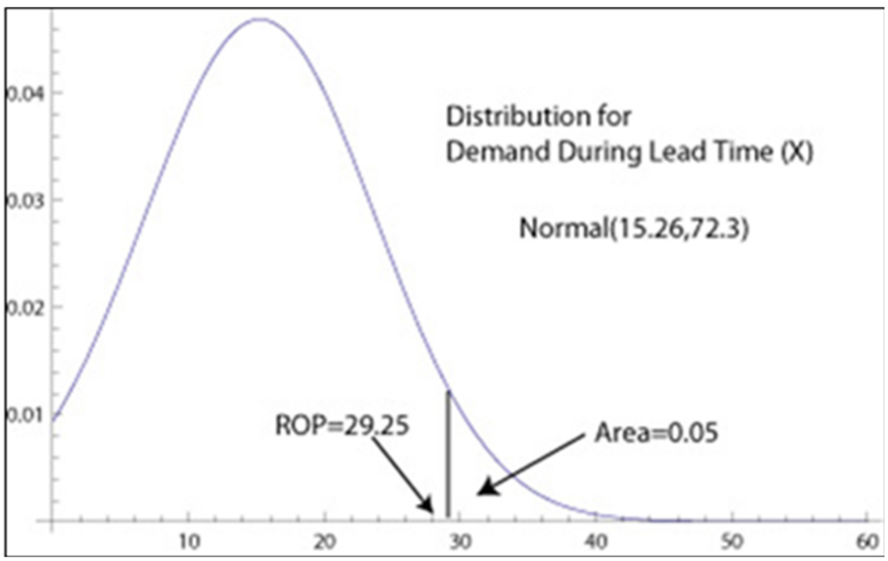

Figure 1. LTD Distribution and Reorder Point

Negative Binomial Approximation

Although the normal approximation to the LTD distribution is popular, there are numerous other approximations that have been suggested in the literature. For example, Taylor (1961) suggested using the negative binomial (NB) distribution for the case where the Poisson distribution is a good fit for DPUT and LT has a gamma distribution. We denote the approximate LTD distribution by $\hat{f}$. Here we assume the NB(r,p) distribution for LTD is

$$\hat{f}(x;r,p) = \frac{\Gamma(x+r)}{x!\cdot\Gamma(r)}(1-p)^r p^x \quad x = 0,1,2,\ldots \tag{3}$$

where $\Gamma(\cdot)$ is the gamma function. Given this formulation, $E(X)=rp/(1-p)$ and $Var(X)=E(X)/(1-p)$. There are two ways of finding a reorder point that will provide an appropriate service level with this NB formulation. Taylor (1961) provided a formula to calculate stockout probabilities as a function of the underlying Poisson and gamma distributions. These can be calculated for possible reorder point values until a suitable value that meets the service level objective is found. Excel can also be used to enumerate the probabilities of achieving a certain service level with various possible values of R. Unfortunately, the built-in NEGBINOM.DIST function only accepts integer values of the r parameter, so these

probabilities must be calculated using the formula in Equation 3 and the GAMMALN function.

For the data in Table 1, we can use the empirical expected value and variance to solve two equations and two unknowns and obtain r = 4.08 and p = 0.79. This NB distribution is shown in Figure 2. The value of R that provides approximately a 95% service level is R = 31.

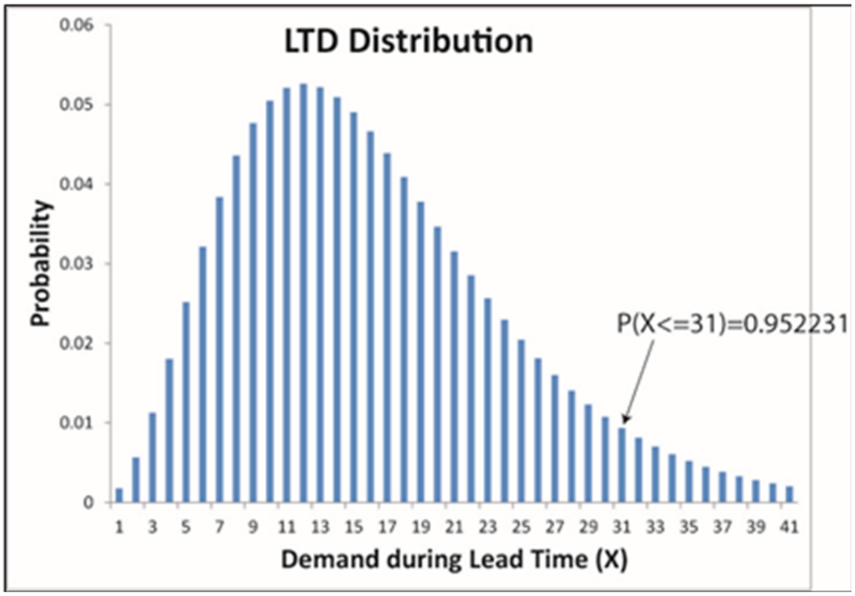

Figure 2. Negative Binomial Distribution for Lead Time Demand

This solution is essentially the same as the one found using Taylor's (1961) analytical formulas. In this case, the Poisson daily demand assumption may be reasonable because $E(D)$ and $Var(D)$ are very similar, a feature of the Poisson distribution.

Mixtures of Truncated Exponentials Approximation

The functional form of some PDFs, such as the negative binomial PDF in Equation 3, does not permit integration in closed-form. The means that the result of an expected value calculation with such a PDF does not have a functional form that can be used for further computation. These calculations could include, for example, building a cost function to perform nonlinear optimization to find optimal inventory policies. One approach suggested to overcome this limitation is the MTE model (Moral, Rumí, & Salmerón, 2001).

An example of a four-piece, two-term (ignoring the constant) MTE function that can be used to model LTD given an LT of L = 3 for the problem in the previous section is

$$\hat{f}_{X|\{L=3\}}(x) = \begin{cases} -0.7148 + 0.6681\exp\{0.0325x\} + 0.000048\exp\{0.989x\} & \text{if } 2.5 \le x < 5 \\ -96.721 - 318.54\exp\{-1.945x\} + 96.76\exp\{0.000128x\} & \text{if } 5 \le x < 8 \\ 0.1383 - (1.63E-06)\exp\{x\} + (2.89E-09)\exp\{1.5x\} & \text{if } 8 \le x < 11.5 \\ -0.0252 + 0.9786\exp\{-0.205x\} & \text{if } 11.5 \le x \le 17.5 \end{cases} \tag{4}$$

This function was found by simulating 500 series of three observations for daily demand from values in Table 1 using a bootstrapping approach. The constants—coefficients on the exponential terms and coefficients on the variable X—were determined by fitting a

function to the simulated histogram. There is an established literature on fitting MTE functions to historical data; in this case, the method suggested by Moral et al. (2002) was utilized. A graphical view of the MTE function overlaid on the simulated histogram is shown in Figure 3.

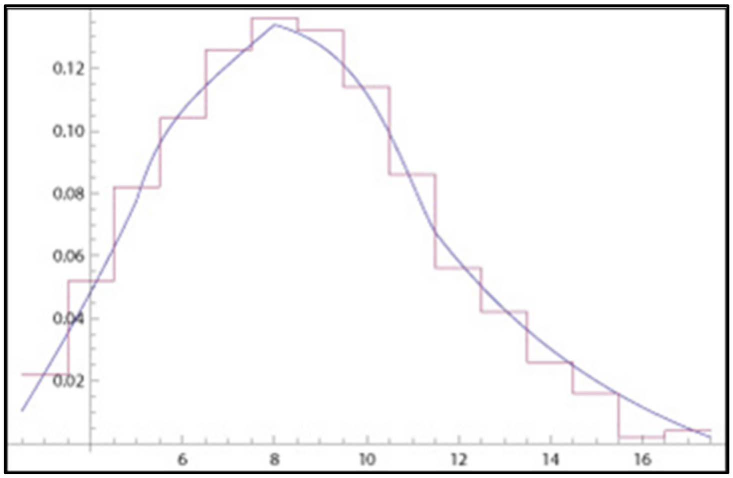

Figure 3. Mixtures of Truncated Exponentials Distribution for Lead Time Demand Given a Lead Time of Three Days

Similar functions $\hat{f}_{X|\{L=l\}}$ can be constructed for the other possible LT values, *L* = 4, 5, and 10. From the data on LT observations in Table 1, we can estimate *P*(*L*=3) = *P*(*L*=4) = *P*(*L*=10) = 0.2 and *P*(*L*=5) = 0.4. A mixture distribution approach (Cobb, 2013) can be employed to find the LTD distribution. Here, the LTD distribution is determined as

$$\hat{f}_X(x) = P(L=3)\cdot \hat{f}_{X|\{L=3\}}(x) + P(L=4)\cdot \hat{f}_{X|\{L=4\}}(x) + P(L=5)\cdot \hat{f}_{X|\{L=5\}}(x) + P(L=10)\cdot \hat{f}_{X|\{L=10\}}(x). \quad (5)$$

The MTE function is shown in Figure 4, overlaid on the previously described NB distribution. This MTE function has 17 pieces and up to six terms in each piece. For illustrative purposes, a continuous NB parameterization is displayed. Because the class of MTE functions is closed under addition, multiplication, and integration (Moral et al., 2001), the mixture distribution resulting from the calculation above is also an MTE function. Thus, it retains the same desirable mathematical properties.

We can perform closed-form integrations of the MTE LTD distribution to find a reorder point that achieves a desired service level. In this case,

$$\int_0^{33.3} \hat{f}_X(x)\, dx \approx 0.95\,, \quad (6)$$

so we can set *R* = 33.3 to obtain a 95% service level.

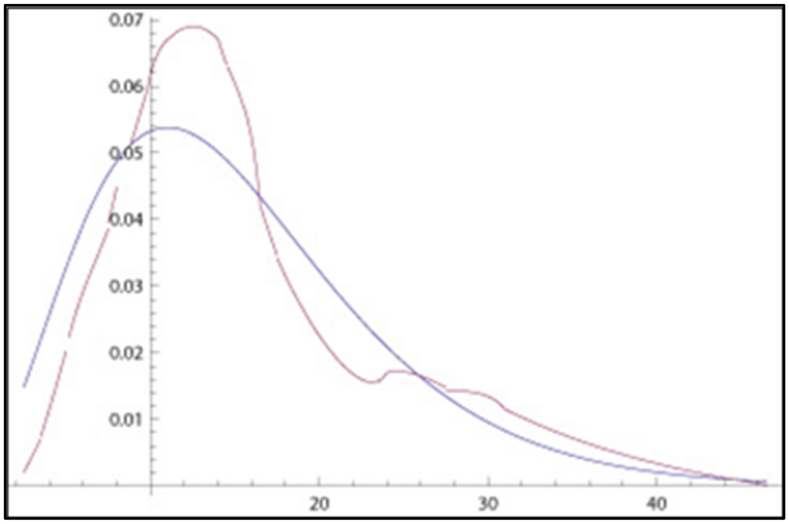

Figure 4. Mixtures of Truncated Exponentials Lead Time Demand Distribution Overlaid on a Negative Binomial Approximation

The next section discusses the use of the MTE function for finding inventory policies in a continuous-review inventory system.

Finding Inventory Policies

Suppose that we want to determine an optimal order quantity and reorder point in a continuous-review inventory system (a "(*Q,R*)" policy). We consider four models that could be used to find the best policy given the data available (see Table 1): (1) a normal approximation to the LTD distribution; (2) the NB approximation to the LTD distribution; (3) the MTE mixture distribution; and (4) a simulation-optimization model that simulates LT and LTD values from the empirical distributions developed from Table 1. We term the latter model the "actual" solution.

A simple cost function with no backordering allowed (Johnson & Montgomery, 1974) for this problem is

$$TC(Q,R) = K \cdot \frac{Y}{Q} + \frac{\pi \cdot Y \cdot S_R}{Q} + h \cdot (0.5Q + R - E(X)) \,. \qquad (7)$$

In this equation, K is the fixed cost per order, Y is the expected annual demand, h is the holding cost per unit per year, and π is the stockout cost per unit. The average inventory includes safety stock of R-$E(X)$. The shape of the distribution for LTD determines the expected shortage per cycle, S_R. For a given reorder point,

$$S_R = \int_R^\infty (x - R) \cdot \hat{f}_X(x)\, dx. \qquad (8)$$

Suppose Y=$E(D)$ · 250 working days = 720, K=30, h=4, and π=5. The key to finding an optimal (*Q,R*) combination is to evaluate S_R as part of constructing the total cost function in Equation 7. With the MTE function, the calculation in Equation 8 can be performed in closed-form, and the result substituted into Equation 7 to obtain a closed-form total cost function. The expected shortage per cycle as a function of R is an eight-piece expression, with selected terms shown below:

$$\hat{S}_R(r) = \begin{cases} -3876.5 + 4.66\exp\{-0.205r\} + 6.31\exp\{-0.172r\} \\ +3888.1\exp\{0.005r\} - 21.82r - 0.04r^2 & \text{if } 16.15 \le r < 16.5 \\ -3890.6 + 4.66\exp\{-0.205r\} + 6.31\exp\{-0.172r\} \\ +3888.1\exp\{0.005r\} + 20.6\exp\{-0.140r\} - 20.64r - 0.07r^2 & \text{if } 16.5 \le r < 17.5 \\ -3889.2 + 6.31\exp\{-0.172r\} + 3888.1\exp\{0.005r\} \\ +20.6\exp\{-0.140r\} - 20.76r - 0.07r^2 & \text{if } 17.5 \le r < 23.5 \\ & \vdots \\ -8.74 + 29.87\exp\{-0.78r\} + 0.28r - 0.002r^2 & \text{if } 31 \le r < 46.5\,. \end{cases} \tag{9}$$

Optimization over the resulting cost function is fast. The example here was solved in Mathematica 9.0 by using the ArgMin function. The results obtained using the four methods under consideration are shown in Table 2. An iterative approach (Hadley & Whitin, 1963) in combination with numerical integration was implemented to find the solutions using the normal or NB approximations. The table shows the values *Q** and *R** which—when implemented simultaneously—minimize annual total cost. The computing (CPU) times required to obtain the solutions are also shown. The simulation-optimization solution was simply stopped after running for several hours, and the values obtained were assumed to be the best possible solution.

Table 2. Results for Inventory Policies Determined Using Four Approaches

Method	*Q**	*R**	*TC*	CPU (sec.)
Normal Approximation	108	25	482.99	3.57
NB Approximation	110	25	482.89	3.76
MTE Mixture Distribution	110	27	481.10	1.26
Simulation-Optimization	108	27	480.82	∞

Table 2 shows that the MTE mixture distribution works equally as well as the other approaches when implemented to obtain an optimal (*Q*,*R*) policy. The next section illustrates that the mixture distribution approach can be used to model more complicated LTD distributions.

State-Dependent Variables

The advantage of the mixture distribution approach (Cobb, 2013) in inventory management problems is that more complex LTD distributions can be constructed by building the model from its components while still maintaining a closed-form representation. In some cases, expert knowledge can be used to assign state-dependent distributions for DPUT and/or LT.

As an illustration, suppose the first row of 10 observations in Table 1 can be associated with replenishment orders where a significant number of missions were canceled due to weather, creating reduced demand. This reduced demand is assumed to occur on 20% of replenishment orders; thus, demand can be considered to have two states: regular (with 80% probability) and low (20% of the time).

To demonstrate another approach to finding MTE approximations, the dataset in Table 1 will be used in this example to first determine a standard PDF that best fits the empirical data for each demand state. In this case, the log-normal distribution with $\mu = 1.03$

and $\sigma^2 = 0.31$ is selected for the regular state, and the LN(0.27,0.19) is chosen for state 2. The demand in each state for a given LT period is then a sum of i.i.d. log-normal random variables. This sum has no known distribution, but approximations for the PDF of a sum of log-normal random variables exist. Following Cobb et al. (2013), the Fenton-Wilkinson approximation (Fenton, 1960) is implemented, and MTE distributions are fit to these approximations for each state and each possible LT value. For state 1 and state 2, these functions are denoted by $\hat{f}^{(1)}_{X|\{L=l\}}$ and $\hat{f}^{(2)}_{X|\{L=l\}}$, respectively. The conditional PDF for LTD given $L = l$ is then calculated as

$$\hat{f}_{X|\{L=l\}}(x) = 0.8 \cdot \hat{f}^{(1)}_{X|\{L=l\}}(x) + 0.2 \cdot \hat{f}^{(2)}_{X|\{L=l\}}(x). \tag{10}$$

The PDF for LTD is constructed as in Equation 5. The new LTD distribution is bi-modal, as shown in Figure 5.

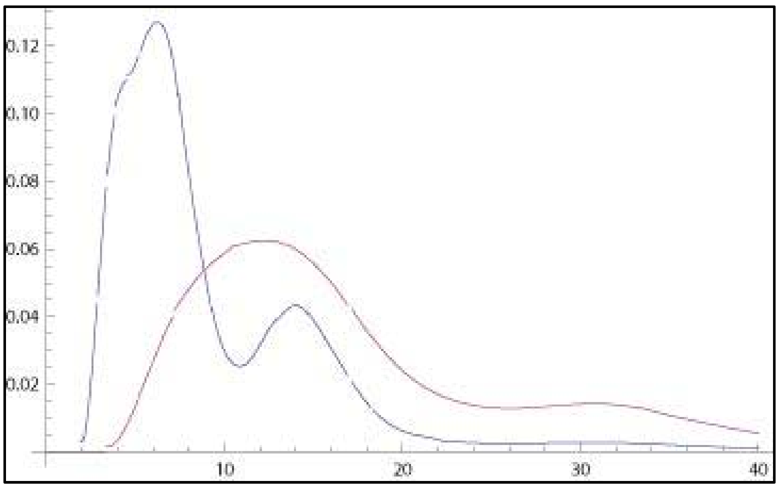

Figure 5. Mixture Distribution for Lead Time Demand With State-Dependent Demand

Suppose the state-dependent, bi-modal distribution shown in Figure 5 is the correct PDF for LTD. Using this distribution as part of the total cost function to find the optimal (*Q,R*) policy results in a 21% savings when compared to implementing the policies found earlier using the MTE distribution shown in Figure 4 (or one of the other approximations). The mixture distribution approach still yields a closed-form function for S_R and the optimization is still fast.

Coordinated Supply Chains

In this section, we consider a two-echelon supply chain, as depicted in Figure 6. A buyer experiencing random demand places its orders for inventory with the supplier.

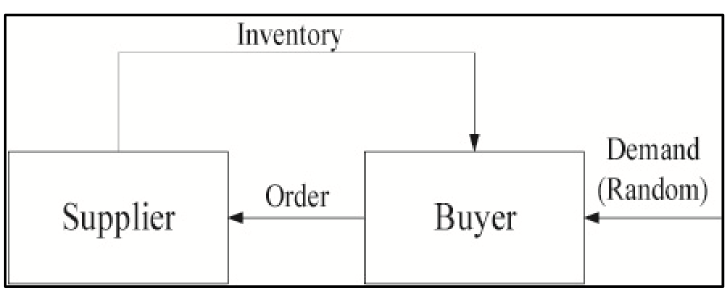

Figure 6. Two-Echelon Supply Chain
(Chaharsooghi & Heydari, 2010)

The cost function for the buyer in this problem is as follows:

$$TC_b(Q,R,V) = (K_b - V) \cdot \frac{Y}{Q} + \frac{\pi \cdot Y \cdot S_R}{Q} + h_s \cdot (0.5Q + R - E(X)). \quad (11)$$

Most of the notation is the same as for the cost function defined in Equation 7. The subscript *b* has been added to the fixed cost per order, annual unit holding cost, and total cost to identify this amount with the buyer. The subscript *s* will similarly represent the seller. The quantity *V* is a rebate provided by the seller to the buyer on a per order basis as an incentive for the buyer to adopt policies that benefit both parties (Cobb & Johnson, 2013). As discussed in the introduction, credit options and price discounts have also been considered in this two-level supply chain as coordination incentives (Chaharsooghi & Heydari, 2010; Chaharsooghi et al., 2011; Li & Liu, 2006).

The cost function for the supplier in this problem is

$$TC_s(Q,N,V) = \left(\frac{K_s}{N} + V\right) \cdot \frac{Y}{Q} + h_s(N-1)0.5Q. \quad (12)$$

In this two-level supply chain model, the buyer selects an order quantity and reorder point. The supplier receives orders of size *Q* from the buyer and purchases inventory from its vendors in a quantity that is an integer multiple *N* of the buyer's order size.

The supply chain can operate in one of three modes. First, the buyer can select Q_d and R_d without considering the effect of its selection on the supplier's costs. In response, the supplier selects N_d to minimize its own costs. This is referred to as the *decentralized* mode, and because there is no coordination, the rebate amount is $V = 0$. Total costs in the supply chain are $TC^d = TC_b(Q_d,R_d,0) + TC_s(Q_d,N_d,0)$. Second, the buyer and supplier can agree on values for Q_c, R_c, and N_c that minimize the sum of the cost functions in Equations 11 and 12. Because the members cooperate fully and are *centralized*, there is again no requirement for the supplier to provide a coordination incentive and $V = 0$. Total costs in this mode are denoted by $TC^c = TC_b(Q_c,R_c,0) + TC_s(Q_c,N_c,0)$.

If the parties are not centralized but can coordinate their policies, the potential exists to divide cost savings of $TC^+ = TC^d - TC^c$. An interval $[V_{min}, V_{max}]$ can be calculated (Cobb & Johnson, 2013) such that any value for the rebate *V* in the interval reduces the total costs in the supply chain to centralized levels. The smallest value of the rebate the buyer will accept can be found by solving $TC_b(Q_c,R_c,V) = TC_b(Q_d,R_d,0)$ for *V*. This value is denoted by V_{min}. The largest value of the rebate the seller will accept can be found by solving $TC_s(Q_c,N_c,V) = TC_s(Q_d,N_d,0)$ for *V*. This value is denoted by V_{max}. For the example in this paper, we assume that if the parties agree to coordinate their policies (and implement Q_c, R_c, and N_c), the value of the rebate they select is $\bar{V} = (V_{min}+V_{max})/2$.

All of the two-echelon supply chain models referenced previously assume that demand for the entire LT period is normally distributed. For the case where both *Q* and *R* are selected to minimize total costs, Charharsooghi and Heydari (2010) derived expressions that state the optimal value for *Q* (in either the decentralized or centralized mode) as a function of the optimal value for *R* (and vice versa) and the standard normal cumulative density function. The optimal values can be found by iterating between these two expressions. The supplier selects the integer value for *N* that minimizes its costs subject to the choices of the buyer.

By implementing the mixture distribution approach, we can develop closed-form expressions for the cost functions in Equations 11 and 12 and find optimal solutions in the same manner as the solutions presented earlier in the paper for the (*Q,R*) inventory model. For illustration, assume $Y = E(D) \cdot 250$ working days = 720, $K_s = K_b = 30$, $h_s = h_b = 4$, and $\pi =$

5. These parameters are the same as used in the earlier example and the supplier has the same cost structure as the buyer (obviously, this may not always be true in practice).

For the previous example, employing the MTE mixture distribution in Figure 4 gives the same results in Table 2 for the decentralized case—Q_d = 110 and R_d = 27. In this mode, the supplier selects the multiple of the buyer's order quantity that minimizes its costs. Because $TC_s(110,1,0)$ = 197 and $TC_s(110,2,0)$ = 316, the supplier selects N_d = 1. Total supply chain costs in the decentralized mode are TC^d = 678.

In the centralized mode, we find the optimal order quantity and reorder point that minimizes $TC_b(Q,R,0)+TC_s(Q,N,0)$ for several possible values of N, then choose the optimal values that give the lowest combined supply chain cost. Again, using the MTE mixture distribution allows the construction of a closed-form total cost function, and optimization over this function in Mathematica is fast. Using the MTE mixture distribution, we find that Q_c=154, R_c=24, and N_c=1. Total supply chain costs in the centralized mode are TC^d= 648. Table 3 summarizes the optimal values for the decision variables in each mode and the total costs for each party and the supply chain. The answers obtained with the mixture distribution approach are compared with those obtained by using the solutions shown by Chaharsooghi and Heydari (2010).

Table 3. Optimal Solutions and Total Costs for the Supply Chain in Three Modes of Operation

Normal	Q	R	N	V	TC_b	TC_s	TC
Decentralized	108	25	1	0	483	200	683
Centralized	151	23	1	0	506	143	649
Coordinated	151	23	1	8.53	466	183	649

MTE Mixture	Q	R	N	V	TC_b	TC_s	TC
Decentralized	110	27	1	0	481	197	678
Centralized	154	24	1	0	507	141	648
Coordinated	154	24	1	8.51	467	181	648

A comparison of the solutions in the decentralized and centralized models shows that the costs in the entire supply chain can be reduced by $TC^+ = TC^d - TC^c = 30$ if the centralized order quantity and reorder point are implemented. However, these policies increase costs for the buyer by 507 - 481 = 26. By using the solutions in Cobb and Johnson (2013) to find the value $\bar{V}$ that divides the cost savings of operating in the centralized mode between the buyer and the seller, the buyer is adequately compensated for increasing its order quantity. The rebate amount for this problem is 8.51 per order cycle. Both members experience costs that are lower than in the decentralized mode.

Conclusions

This paper serves as an introduction to using a mixture distribution approach to modeling the probability density function for LTD in problems where a continuous review inventory system is implemented. First, construction of the lead time distribution was illustrated. This distribution was then utilized to determine optimal order policies in cases where a buyer makes its decisions alone, and then when members of a two-level supply chain coordinate their actions.

This paper represents the first stage of the research to be conducted for the project entitled “Modeling Uncertainty in Military Supply Chain Management Decisions,” which has been funded under BAA Number NPS-BAA-12-002 through the Naval Postgraduate School (Grant N00244-13-1-0014). For the expanded project, inventory requisition data for a five-year period has been obtained from the Air Force Standard Base Supply System for a power supply unit used on F-15 and F-16 aircraft. The techniques presented in this paper will be compared to an approach currently used by the Air Force that employs a negative binomial approximation to the lead time demand distribution. The comparison will be similar, but the hypothetical data in this paper will be replaced by the actual historical data provided by the Air Force.

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Improving Multi-Component Maintenance Acquisition With a Greedy Heuristic Local Algorithm

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Abstract

As many large-scale DoD systems age, and due to budgetary and performance efficiency concerns, there is a need to improve the decision making process for system sustainment, including maintenance, repair, and overhaul (MRO) operations and the acquisition of MRO parts. To help address the link between sustainment policies and acquisition, this work develops a greedy heuristic–based local search algorithm to provide a system maintenance schedule for multi-component systems, coordinating recommended component maintenance times to reduce system downtime costs thereby enabling effective acquisition.

Introduction

Large organizations such as the Department of Defense (DoD) have to devote a significant amount of their budgets to system maintenance. According to a 2007 Government Accountability Office (GAO) report, the DoD spends approximately 40% of its budget on operations and management (O&M) activities to ensure system readiness ($209.5 billion in 2005). GAO reported that since fiscal year 2001, the DoD's O&M costs are increasing, and the Air Force, in particular, had to increase its O&M cost by 29%. As many large-scale DoD systems age, and due to budgetary and performance efficiency concerns, there is a need to improve the decision making process for system sustainment, including maintenance, repair, and overhaul (MRO) operations and the acquisition of MRO parts.

The DoD's acquisition costs have seen growth in recent years (GAO, 2013). The GAO (2013) recommended that the DoD improve its strategic management plan to make maintenance supply chain operations more cost effective. Further, the DoD was advised to "link acquisition and sustainment policies" for depot maintenance improvement and ultimate cost efficiency (GAO, 2011). To help address the link between sustainment policies and acquisition, this work develops a framework to provide a system maintenance schedule for multi-component systems. As the multiple components of a system have their own

lifecycles, an efficient means to schedule overall system maintenance should consider these individual components to maximize long-term availability of the system. This framework coordinates recommended maintenance times, such as those found as a result of reliability centered maintenance (RCM) or from original equipment manufacturer (OEM) suggestions, to formulate a system-level maintenance schedule for a finite time horizon. Such a framework will increase the acquisition efficiency of components with a more effective system-level maintenance schedule.

With the recent computational advances, several preventive maintenance models have been proposed for complex multi-component systems considering component interactions. In the preventive maintenance scheduling problem (PMSP), different kinds of component interactions are taken into account. Interaction among components can be economic dependence, structural dependence, and/or stochastic dependence (Thomas, 1986). In a basic sense, economic dependence among system components means that the cost of joint repair is different from cost of individual repair (Dekker, Wildeman, & van der Duyn Schouten, 1997), suggesting that performing repair operations for multiple components at once can be done with less expense than for single components.

Researchers have considered different model formulations, as well as solution techniques, to address preventive maintenance decision making. Stinson and Khumawala (1987) formulated a heuristics-based mixed integer linear program (MILP) model for a finite horizon preventive maintenance problem for maintaining machines in series. Budai, Huisman, and Dekker (2006) proposed a heuristics-based MILP solution for scheduling railroad network maintenance. Other few noteworthy approaches are Bayesian network model (Celeux, Corset, Lannoy, & Ricard, 2006), goal programming for a multi-objective problem (Bertolini & Bevilacqua, 2006), and dynamic programming (Dekker, Wildeman, & Van Egmond, 1996).

In terms of algorithm development, Dekker, Smit, and Losekoot (1991) presented an optimal maintenance model using a set-partitioning algorithm for multiple maintenance activities. One downside of their model was that they considered each activity time to be negligible relative to the total planning horizon. Later Dekker et al. (1996) solved the above-mentioned problem with a dynamic programming formulation, concluding that the dynamic algorithm is a good heuristic for rolling horizon–based problems which can incorporate short-term system information for decision support. Dekker et al. (1997) provided a review of maintenance models for multi-component systems, which covered economically dependent systems. The Markov decision chain–based approach was also studied by Dekker et al. (1996) for the multi-activities maintenance problem which was applicable to systems consisting of many components. Previous Markov chain–based models were limited to few components. An opportunistic maintenance policy was modeled by Gürler and Kaya (2002) and van der Duyn Schouten and Vanneste (1993) for identical multi-component systems. Sheu et al. (1996) modeled a similar kind of problem with a two-stage opportunistic policy. In the case of non-identical components maintenance, the tradeoff between the repair cost of one component versus another should be considered, including the resulting increase in the complexity of the model.

PMSP remains a very active area of research. Little work in this field has used heuristics and meta-heuristics based methodologies to model preventive maintenance framework (Nicolai & Dekker, 2008). A new meta-heuristic based on a genetic algorithm was applied in train maintenance scheduling problems by Sriskandarajah, Jardine, and Chan (1998), primarily optimizing cost. Nicolai and Dekker (2008) presented a review of preventive maintenance and recommended that more researches need to be done in this area developing more heuristic and meta-heuristic approaches like simulated annealing and

local search. Meta-heuristic based algorithms have proven very successful for flowshop scheduling problems (Pan & Ruiz, 2012), which have similar characteristics to preventive maintenance scheduling.

This work presents a greedy heuristic–based local search algorithm for preventive maintenance of multiple components which would be a new contribution in this field of research. We develop a local search–based algorithm to minimize the total maintenance cost of a system over a finite planning horizon. This paper is organized as follows. The Methodological Development section provides a detailed description of the different components and procedure of our proposed schedule algorithm for a multi-component system. The next section, Greedy Heuristic with Local Search Algorithm, provides experimental results for a presented multi-component scheduling problem. We conclude our paper with the Experimental Results section and some concluding remarks.

Methodological Development

Here we develop a new formulation and solution algorithm to address preventive maintenance scheduling for a multi-component system. It is assumed that maintenance results in a "good as new" condition.

Baseline individual component maintenance times for planning horizon T (i.e., system-in-use time) are known and recommended based on a mean time between failure (MTBF) calculation (e.g., by RCM or OEM calculations). We assume these component maintenance times are given in their in-use-time or up-time. Our goal is to suggest to alter the recommended maintenance schedule for a multi-component system in a joint manner for as many components as possible. Performing many individual maintenance events at recommended schedules can potentially lead to cost savings due to reduced setup costs and reduced downtime. However, varying too far from recommended MTBF guidance can lead to unnecessary maintenance (in the earliness situation) and risk of failure (in the tardiness situation). *Earliness* refers to the performance of maintenance earlier than recommended, with *tardiness* representing the performance of maintenance at a time later than recommended. As such, there are penalties associated with both earliness and lateness, as well as a penalty for system downtime while maintenance is being performed.

Different potential maintenance schedules can be compared and evaluated using a penalty function approach (Yousefi & Yosuff, 2013). In this approach, a penalty function can be achieved by quantifying setup-related costs into setup penalties, downtime costs into downtime penalties, related expense (i.e., costs of unnecessary maintenance) of earliness into earliness penalties, and potential failure costs of tardiness situation into tardiness penalties. By implementing this approach, a maintenance schedule can be found which will minimize these penalties. These penalties, as well as other notation, are defined as follows:

T	Planning horizon
n	Number of components in the system
C_S	System setup penalty per maintenance
$T_{m,l}^k$	*k*th maintenance time for component *l*
$C_{E,l}$	Earliness penalty for component *l*, per unit time
$C_{L,l}$	Tardiness penalty for component *l*, per unit time
C_D	System downtime penalty per unit time
$T_{r,l}$	Component maintenance duration for component *l*
δ	Construction phase time-span parameter where $\delta \epsilon (0, 1]$
γ	Joint maintenance time parameter $\gamma \epsilon (0, 1]$
Δ_j	Deviation of individual component maintenance times from *j*th system maintenance
T_{max}	Maximum time-span of construction phase
T_c	Construction phase time-span
T_{m1}	Set of first component maintenance time
T_{m2}	Set of second component maintenance time
π^c	Candidate solution
π^d	Discard solution
S^c	Candidate combination set
S^d	Discard set
S	Algorithm solution vector

Decision variables for the scheduling formulation include the following:

t_m^j	*j*th system maintenance time
R	Total number of system maintenance events scheduled in planning horizon T
x_l^j	If feature earliness is present in component *l* for maintenance *j* ($x_l^j = 1$) or not ($x_l^j = 0$)
y_l^j	If feature tardiness is present in component *l* for maintenance *j* ($y_l^j = 1$) or not ($y_l^j = 0$)
z_l^j	If component *l* should be repaired at time t_m^j ($z_l^j = 1$) or not ($z_l^j = 0$)

Performing joint repair has the potential to save maintenance cost because for many multi-component systems it is possible to perform component maintenance simultaneously. Thus total repair time for joint maintenance depends on individual instance and can be predicted from previous system maintenance data. Considering all these penalties, our goal is to develop an algorithm that will schedule system maintenance time such that total penalties of system maintenance are minimized over the given planning horizon *T*. The basic optimization problem is conceptualized in Equation 1, where $C_S R$ represents total setup penalties for planning horizon *T,* and C_l^j represents penalties associated with *j*th system repair of component *l*. C_l^j includes penalties for downtime, earliness, and tardiness for component *l* during *j*th system maintenance. Decision variable z_l^j determines whether component I will be repaired at *j*th system maintenance.

$$\min_{z_l^j} C_S R + \sum_{l=1}^{n} \sum_{j=1}^{R} C_l^j \, z_l^j$$
$$\text{s.t.} \quad z_l^j \in \{0,1\} \qquad (1)$$
$$\text{MRO requirement constraints}$$

Equation 2 presents the actual objective function and constraints for the problem above.

$$\min_{t_m^j} \; C_S R + \sum_{l=1}^{n} \sum_{j}^{R} \left| T_{m,l}^k - t_m^j \right| C_{E,l} \, x_l^j + \sum_{l=1}^{n} \sum_{j}^{R} \left(T_{m,l}^k - t_m^j \right)^2 C_{L,l} \, x_l^j + \sum_{l}^{n} \sum_{j}^{R} C_D \gamma \, T_{r,l} z_l^j$$
$$\begin{aligned} \text{s.t.} \quad & R > 0 \\ & t_m^j > 0 \\ & x_l^j \in \{0,1\} \\ & y_l^j \in \{0,1\} \\ & z_l^j \in \{0,1\} \\ & \gamma \in (0,1] \end{aligned} \qquad (2)$$

One of the decision variables is the system-in-use time at which system maintenance should be performed. As maintenance scheduling is multistage (e.g., maintenance is a repeated event), the time at which maintenance is scheduled for iteration *j* is t_m^j This work will solve Equation 2 over a finite time horizon for several MRO stages, finding a series of t_m^j values at which maintenance should occur. OEM-recommended individual component maintenance times are denoted by $T_{m,l}^k$. Here t_m^j values attempt to coordinate the downtime of several components to maximize long-term availability of the system. Equation 2 conceptualizes an availability cost problem, where z_l^j determines whether component *l* should be repaired at time t_m^j according to the cost function which penalizes unavailability. Equation 2 also attempts to improve upon $T_{m,l}^k$ to minimize the deviation of individual component maintenance times from system maintenance time, found in the neighborhood of $T_{m,l}^k$. As such, this work provides the maintenance schedule for the system, whether the *j*th maintenance operation will repair an optimal subset of the *n* components in the system.

Elements of the above formulation are given more detail as follows. The actual structure of the penalty function here can vary due to decision maker preferences.

Penalty Function

Our objective is to minimize total system maintenance penalty over a finite time horizon *T*. Our penalty function is the presented objective function in Equation 2. This total penalty function consists of system setup penalty, system downtime time penalty, and penalty for any deviation of individual component maintenance times from system maintenance time. Note that we are not penalizing for the cost of performing actual repair, including the cost of acquisition and the cost of labor, among others, under the assumption that this cost is the same for individual repair and joint repair.

System Setup Penalty

The setup penalty component in Equation 3 accounts for the time to arrange for system maintenance. A system setup penalty penalizes all associated costs for maintenance setup, charged only once regardless of the number of multiple components involved in a maintenance work. Not included is component setup time, as that is not expected to be a factor in determining individual or joint maintenance; any maintenance performed on a component would require component setup time. Fixed system penalty per maintenance work C_S is known.

$$\text{System setup penalty} = C_S\, R \tag{3}$$

Earliness Penalty

There is a penalty for executing the component maintenance at a time other than the maintenance recommended by the OEM. If system maintenance is scheduled earlier than recommended individual component maintenance, then there is a penalty for early maintenance work for that component. This penalty attempts to penalize the performance of maintenance unnecessarily too far in advance of the OEM recommendation, and it is a function of (i) the total amount of earliness determined by $\left|T_{m,l}^{k} - t_m^j\right|$ (ii) the earliness penalty $C_{E,l}$, and (iii) whether component *l* maintenance is performed early, determined by x_l^j.

$$\text{Earliness penalty} = \sum_{l=1}^{n} \sum_{j}^{R} \left|T_{m,l}^{k} - t_m^j\right| C_{E,l} x_l^j \tag{4}$$

Tardiness Penalty Cost

If system maintenance is scheduled later than individual component maintenance, then there is a penalty for late maintenance work for that component. This penalty is a function of the deviation of recommended individual component maintenance times from the actual system maintenance time. The penalty is higher for tardiness than earliness here due to aversion to performing maintenance later than recommended. This is represented, in part, by the square on the amount of tardiness time, $\left(T_{m,l}^{k} - t_m^j\right)^2$. Other elements include tardiness penalty $C_{L,l}$ and whether component *l* maintenance is performed after the OEM suggested maintenance time, determined by y_l^j.

$$\text{Tardiness penalty} = \sum_{l=1}^{n} \sum_{j}^{R} \left(T_{m,l}^{k} - t_m^j\right)^2 C_{L,l}\, y_l^j \tag{5}$$

System Downtime Cost

There is a cost associated with system downtime due to an unproductive or idle system. The system downtime penalty per unit time C_D is known. Expected component maintenance duration for component *l* is parameterized as $T_{r,l}$. Parameter γ represents the percentage of total expected component maintenance duration (i.e., $\sum T_{r,l}$ for all *l* that are present in *j*th system maintenance) that would be the expected joint maintenance duration for *j*th system repair. We assume this γ value to be constant for all iterations. The value of joint maintenance time parameter γ can be chosen from the historical data of a related system such that $\gamma \epsilon (0, 1]$. The higher the γ parameter value, the higher the downtime maintenance cost would be. Higher γ means less time savings in joint repair compared to

separate maintenance. γ reaches a value of 1 when the expected joint repair time is equal to the summation of individual component repair times; those are present in *j*th joint repair. In other words, the expected downtimes are the same for joint repair and separate repair when $\gamma = 1$.

This value defines joint maintenance times for a multi-component system. The term z_l^j determines whether the *j*th maintenance operation for component *l* is performed.

$$\text{System downtime cost} = \sum_l^n \sum_j^R C_D \gamma\, T_{r,l} z_l^j \tag{6}$$

Construction Phase Time-Span Parameter (δ)

At the beginning, construction phase time-span parameter delta ($\boldsymbol{\delta}$) is chosen such that $\boldsymbol{\delta} \in (0, 1]$. This $\boldsymbol{\delta}$ value is kept constant throughout the algorithm. Discussed later, the algorithm solution is very sensitive to this delta value and needs to be tuned according to individual instance. A detailed sensitivity analysis and tuning recommendation of $\boldsymbol{\delta}$ are presented later.

Weibull Distribution

The recommended individual maintenance times are assumed here to be the MTBF from a two-parameter Weibull distribution. The Weibull distribution is well known in reliability analysis in describing the time between failures for components. MTBF for a Weibull distribution is found in Equation 7, where β is the shape parameter, η is the scale parameter, and Γ is the gamma function.

$$\text{MTBF} = \eta\Gamma(1 + \frac{1}{\beta}) \tag{7}$$

Greedy Heuristic With Local Search Algorithm

The maintenance optimization model described previously is solved with a proposed iterative Greedy Heuristic with Local Search Algorithm (GHLSA). The proposed algorithm is similar to the generic structure of the Greedy Randomized Adaptive Search Procedure (GRASP; Feo & Resende, 1995]. In contrast to the two phases of GRASP, our proposed algorithm has three phases: (1) a construction phase, (2) an improvement phase, and (3) a local search phase. In the GRASP algorithm, the initial solution is constructed using a randomized sampling technique, whereas our algorithm uses a greedy heuristic to construct an initial partial solution. We also use an additional improvement phase, where the greedy heuristic–based improvement ends. An overview of the proposed algorithm is presented in Figure 1.

```
procedure GHLSA ()
    begin
        I ← InputInstance { };
        for GHLSA stopping criterion not satisfied →
            π_j^0 ← InitialPartialSolution (I,δ);
            π_j' ← GHBI (π_j^0);
            π_j'' ← LocalSearch (π_j');
            UpdateSolution (π_j'');
        endfor
        return OptimalSolutionFound;
    end GHLSA;
```

Figure 1. Pseudo-Code Overview of the Proposed Greedy Heuristic With Local Search Algorithm (GHLSA)

In brief, the three phases of the algorithm achieve the following:

1. *The construction* phase determines how many components in the system should be initially examined to include in system maintenance of multiple components and an initial estimate for the time at which that multi-component maintenance operation should occur.
2. *The improvement phase* improves the construction phase result by dividing the set of multiple components into two sets (a *candidate set* and a *discard set*) to determine whether dividing the maintenance operation will produce a lower penalty than the construction phase. This phase iterates by removing a component out of the candidate set one at a time and placing it in the discard set and calculating penalty improvement.
3. *The local search phase* focuses on the resulting candidate set from the improvement phase and iterates across the different times associated with recommended component maintenance to balance the penalties of earliness and tardiness of individual components.

These three phases are performed at each iteration *j*, thereby resulting in the set of components involved in the *j*th system maintenance operation and the time at which the *j*th system maintenance operation should be performed. The algorithm stopping criterion is the pre-determined planning horizon *T*. Let *I* be the set of discrete time periods where each element represents recommended (e.g., from RCM or OEM suggestions) repair times of a component during planning horizon *T*.

The final solution of this algorithm is essentially an *R × 1* vector for all system maintenance operations, where each element of the vector represents the recommended *j*th system maintenance. The result of each iteration *j* is referred to as the *j*th partial solution of the over final solution. Each element of the algorithm solution is comprised of two parts: π_j [0] refers to the set of repair times $\left\{T_{m,\mathrm{A}_1}^{a_1}, \dots, T_{m,\mathrm{A}_n}^{a_n}\right\}$ of components to be performed jointly at the *j*th system maintenance operation (where $T_{m,\mathrm{A}_n}^{a_n}$ is the a_n maintenance operation for component A_n), and $\pi_j[1]$ refers to the recommended time t_m^j at which the *j*th system

maintenance is to be performed. For example, $\pi_j = \left[\pi_j[0], \pi_j[1]\right] = \left[\{T^a_{m,\mathrm{A}}, T^b_{m,\mathrm{B}}, T^c_{m,\mathrm{C}}\}, t^j_m\right]$ suggests that the *a*th maintenance operation of component A, the *b*th maintenance of component B, and the *c*th maintenance of component C will all be performed jointly at time t^j_m, the time chosen for the *j*th system maintenance operation to occur. Thus during each iteration of this algorithm, it finds an element which we refer to as a partial solution for algorithm solution set. At each iteration *j*, the three phases of the algorithm are performed, each of which is explained in detail subsequently. Through these three phases of construction and improvement, a partial solution is found, and this partial solution is then added to the solution set to update the algorithm solution for the scheduling maintenance problem. This iterative process is completed when the solution is found for the given planning horizon.

Using input instance *I* and chosen value δ, an initial partial solution π^0_j is created in the construction phase. During the improvement phase, this initial partial solution π^0_j is improved using greedy heuristic–based procedure GHBI. This improved partial solution is represented by π'_j.. During the local search phase of the jth iteration, partial solution π'_j.is further improved using the LocalSearch procedure, and the third phase returns the final partial solution $\pi^{"}_j$. After finding the best partial solution $\pi^{"}_j$ in the third phase, we need to update the existing algorithm solution *S* and input set *I*. This partial solution " is then added as the jth element to solution vector *S*, to update the algorithm solution. All scheduled component maintenance times $T^k_{m,l}$ at iteration *j* are removed from set *I* for the next $(j + 1)$st iteration, and the rest of the unscheduled component repair times of set *I* are updated according to their earliness or tardiness deviation for *j*th system maintenance.

Phase 1: Initial Partial Solution Construction

At each iteration *j*, the first phase is a construction phase where the initial partial solution is generated. General pseudo-code for this partial solution construction phase is presented in Figure 2. $T_{\max}$ is the time duration which expresses the maximum time-span which includes all the component repair times to be initially considered for repair during jth system maintenance. The construction phase time-span is selected according to the δ value, which reduces the length of time originally considered by proportion δ. All component repair times $T^k_{m,l}$during time-span T_c are included in the joint repair component set for the initial partial solution π^0_j for iteration *j*. This constructs the first part of the initial partial solution, π^0_j[0].

Step 1.1. Calculate T_{max}

The maximum time-span of construction phase $T_{\max}$ needs to be calculated. This $T_{\max}$ value represents the time duration between the recommended time for the earliest first repair of all components and the recommended time for the earliest second repair. Let the sets of first and second repair times of each component out of all unscheduled maintenance times be T_{m1} and T_{m2}, respectively. The minimum value of set T_{m1} is denoted by EarliestFirstRepairTime, and the minimum value of set T_{m2} is expressed by EarliestSecondRepairTime in the pseudo-code in Figure 2. The absolute value of their difference is the value of time-span $T_{\max}$

Step 1.2. Calculate T_c

Construction phase time-span $T_c$can be calculated by multiplying the value of the maximum time-span of construction phase $T_{\max}$ by δ. In a sense, δ is the scope of granularity. A small value of δ suggests a tight granularity of the maintenance option set,

meaning that a shorter time frame will be considered for T_c with which to consider multiple component maintenance options. For a larger value of δ, $T_{\max}$ approaches $T_{\max}$ value. And T_c is equal to $T_{\max}$ when $\delta = 1$.

Step 1.3. Partial Solution Component Set

Insert all recommended component maintenance times $T_{m,l}^{k}$ that are originally scheduled during construction phase time-span T_c into the joint repair component set $\pi_j^0[0]$ of the initial partial solution π_j^0. If there are n_{m1} elements in set T_{m1}, then it would take n_{m1} iterations to construct the initial partial solution component set.

The time at which system maintenance is performed on the components in $\pi_j^0[0]$ constitutes the second part of the initial partial solution, $\pi_j^0[1]$, which can be chosen according to several heuristics including

- the mid-point of time-span T_c,
- a component repair time of component set $\pi_j^0[0]$ where the deviation Δ_j is minimized, or
- the earliest component repair time (i.e., the minimum value of component set π_j^0 [0]).

In our implementation, the third heuristic above is used to construct the later part of the initial partial solution. That is, the second part of the initial partial solution, π_j^0 [1], is chosen according to the heuristic convention of scheduling system repairs at the earliest component repair time. Thus, this phase schedules all possible component maintenance during time-span T_c at the earliest possible time to produce an initial partial solution.

```
procedure InitialPartialSolution (I,δ)
    begin
        π_j^0 ← { };
        T_max ← |EarliestFirstRepairTime - EarliestSecondRepairTime |;
        n_m1 ← |T_m1|
        T_c ← δ * T_max
        for  i ← 1 to n_m1 do
            if T_m1[i] < T_c then
                π_j^0 ← π_j^0  U  T_m1[i] ;
            endif
        endfor
        return π_j^0;
    end  InitialPartialSolution;
```

Figure 2. Pseudo-Code for GHLSA Phase 1, the Partial Solution Construction Phase

Phase 2: Greedy Heuristic-Based Improvement (GHBI)

During the second phase of iteration *j*, the algorithm improves the initial partial solution π_j^0 constructed in Phase 1, focusing primarily on the components in $\pi_j^0[0]$ to be repaired jointly (e.g., $\{T_{m,\mathrm{A}}^{a}, T_{m,\mathrm{B}}^{b}, T_{m,\mathrm{C}}^{c}\}$). A search is performed in the neighborhood of π_j^0 to

find a better partial solution. This combination of component repair times is improved according to a greedy heuristic of removing the last-one-out (i.e., latest component repair time) from existing combinations.

Let the initial partial solution π_j^0 be the existing partial solution π_j' (i.e., *j*th solution element). If there are n_p elements in the joint repair component set (π_j^0[0]) of the existing partial solution, then there would be n_p possible combinations of component sets that can be created according to the last-one-out greedy heuristic. The best combination set among n_p possible combinations is selected in $(n_p - 1)$ iterations. At each iteration of the $(n_p - 1)$, two temporary partial solution elements called *candidate solution* π^c and *discard solution* π^d (i.e., temporary *j*th and (*j*+1)st) are generated from existing partial solution π_j'. The best candidate solution is selected as the new existing partial solution π_j' according to an acceptance criterion. Each iteration of this greedy heuristic–based improvement method, which is the ImproveCombination procedure in Figure 3, is described below.

Step 2.1. Determining $\boldsymbol{\pi_j'}[\mathbf{0}]$

The first part of a solution element presents the component repair times to be repaired jointly. Improved combination of this joint repair component set is searched using the last-one-out heuristic. To generate an improved combination of the *j*th solution element, two sets (i.e., candidate combination set S_c and discard set S_d) are created from the existing joint repair component set. The candidate set will eventually be repaired during the *j*th iteration, and the discard set will be saved for the (*j* + 1)st iteration or beyond. Let the existing joint repair component set be the initial value of candidate combination set S_c. By applying the last-one-out greedy heuristic (i.e., latest component repair time), a new discard set S_d is created. To generate the discard set S_d, the latest component repair time (i.e., max S_c) is removed from candidate solution set S_c and inserted into discard set S_d. Candidate set S_c and discard set S_d construct the first part of the candidate solution π^c and discard solution π^d respectively (i.e., $\pi^c[0]$ and $\pi^d[0]$).

Step 2.2. Determining $\boldsymbol{\pi_j'}[\mathbf{1}]$

The time at which the elements of the candidate solution $\pi^c[0]$ are repaired is found from the earliest component repair time heuristic for the set (i.e., min S_c). This time of repair is $\pi^c[1]$. Similarly, the components in discard solution $\pi^d[0]$ are repaired at $\pi^d[1]$, or min S_d. Other heuristics that could be used in this step were presented in step 3 of the previous phase.

Step 2.3. Acceptance Criterion

The candidate solution is selected as the existing partial solution π_j', according to the acceptance criterion of the minimum penalty function. The existing candidate solution is chosen as the partial solution π_j' if the combined penalty function value of candidate and discard solutions is less than the penalty function value of the existing partial solution π_j'.

Figure 3 presents the procedure of developing new combination set according to the greedy heuristic.

```
procedure ImproveCombination ( π_j^0)
   begin
      CurrentPenalty ← PenaltyFunction (π_j^0);
      π_j' ← π_j^0 ;
      π_c ← [ ] ;
      π_d ←[ ] ;
      S_c ← π_j^0[ 0 ];
      S_d ← { };
      n_p ←|π_j^0[ 0 ]|;
      for i ← 1 to (n_p -1) do
            S_c ← remove last component repair time and insert it in S_d ;
            π_c ←[{ S_c }, min ( S_c ) ] ;
            π_d ←[{ S_d }, min ( S_d ) ] ;
            NewPenalty ← PenaltyFunction (π_c )+ PenaltyFunction (π_d);
            if NewPenalty < CurrentPenalty then                % Acceptance criterion
                  π_j' ←π_c ;
                  CurrentPenalty ← PenaltyFunction (π_c ) ;
            endif
      endfor
      return π_j' ;
   end ImproveCombination ;
```

Figure 3. Pseudo-Code for Improving Combination Stage

As long as the number of elements n_p of existing partial solution π_j' is greater than 1 and minimizes the penalty function value, π_j' is divided into two new parts: candidate solution π^c and discard solution π^d. This iterative improvement is performed in the *while* loop presented in procedure GHBI. Figure 4 describes the procedure GHBI using pseudo-code.

```
procedure GHBI (π_j^0)
    begin
        π_j' ← π_j^0 ;
        CurrentPenalty ← PenaltyFunction (π_j^0);
        n_p ← |π_j^0[0]|;
        NewPenalty ← 0;
        while (NewPenalty < CurrentPenalty and n_p  > 1 ) do
            CurrentPenalty ← PenaltyFunction ( π_j' );
            π_j' ← ImproveCombination ( π_j' );            % Using greedy heuristic last-one-
            out
            NewPenalty ← PenaltyFunction ( π_j' );
              n_p ← | π_j' [0]| ;
        endwhile
        return  π_j' ;
    end GHBI;
```

Figure 4. Pseudo-Code for GHLSA Phase 2, the Greedy Heuristic-Based Improvement Phase

Phase 3: Local Search-Based Improvement

In the last phase of system maintenance iteration *j*, an improved partial solution is selected by searching the neighborhood of current partial solution π_j', building the best candidate set of components repair at the *j*th iteration. Let this improved partial solution be π_j'' and its initial value be π_j'. Emphasis in this third phase is placed primarily on searching different values of t_m^j in the neighborhood of $\pi_j'[1]$ to determine when the *j*th maintenance operation should occur. The pseudo-code for this local search phase is shown in Figure 5. During this improvement phase, t_m^j iteratively takes the values of component maintenance time generated from the final combination set $\pi_j'[0]$ during the previous phase and creates a temporary partial solution. During this iterative process, the partial solution is updated according to the penalty function in Equation 2. According to our selected method, it takes n_p iterations to search the neighborhood of $\pi_j'[1]$, if the number of elements in combination set $\pi_j'[0]$ is n_p. At each iteration of n_p, a new temporary partial solution called *temp* is generated. Steps of each iteration are as follows.

Step 3.1. Determining $\pi_j''[0]$

The joint repair component set comprising $\pi_j''[0]$ takes the value of the final combination set (i.e., $\pi_j'[0]$) found in the second phase.

Step 3.2. Determining $\pi_j''[1]$

During this improvement phase $temp[1]$ (i.e., t_m^j) iteratively takes the values of the component maintenance time generated from the final combination set $\pi_j'[0]$ during the previous phase. At iteration n_p, t_m^j would take the value of n_pth element of combination set $\pi_j'[0]$.

Step 3.3. Acceptance Criterion

The acceptance criterion is the value of the penalty function presented in Equation 2. At each iteration of n_p, the temporary partial solution *temp* is selected as the new existing partial solution only if the new temporary partial solution minimizes the penalty function value.

At the end of n_p iterations, the LocalSearch procedure returns the best value found in the search. The return value, π_j'', of this local search–based improvement is the partial solution representing the *j*th element of the final solution vector.

```
procedure LocalSearch (π'_j)
    begin
        π"_j ← π'_j ;
        CurrentPenalty ← PenaltyFunction (π'_j);
        NoOfElement ← |π'_j [0]|;
        if NoOfElement  > 1 then
            for i ← 1 to NoOfElement do
                temp ← π"_j ;
                temp [1] ← π'_j [0] [ i ];
                NewPenalty ← PenaltyFunction (temp);
                if NewPenalty < CurrentPenalty  then
                    π"_j [1] ← π'_j [0] [ i ];
                    CurrentPenalty = PenaltyFunction (π"_j);
                endif;
            endfor;
        endif;
        return π"_j ;
    end LocalSearch;
```

Figure 5. Pseudo-Code for the GHLSA Phase 3, the Local Search Phase

Experimental Results

An example problem briefly illustrates the algorithm.

Problem Specification

Our example problem addresses 10 components in a multi-component system. We assume the initial start time TNOW is zero. We assumed the earliness penalty and tardiness penalty values to be equal and same for all components (i.e., deviation penalty C_p). Maintenance duration $T_{r,l}$ is assumed to be 5 time units for all components. The recommended individual maintenance times of these components are assumed here to be the MTBF from a two-parameter Weibull distribution with shape parameters (β) and scale parameters (η). The assumed values of planning horizon, setup cost, downtime cost per unit time, earliness penalty, and tardiness penalty are presented in Table 1.

Original Case

The original case follows a simple procedure for maintenance. Each system maintenance operation is performed at the earliest component repair time (i.e., min $T_{m,l}^{k}$) out of unscheduled component maintenance times. It is assumed that all repair times are in the system repair window (i.e., min $[T_{m,l}^{k} + T_{r,l}]$) and will be scheduled to be repaired at the same time. We used the same penalty function to calculate the objective function value for the original case. Note that the tardiness penalty will always be zero in the original case instance, as system maintenance is done at the earliest component repair time and there is no push back of component maintenance.

Table 1. Parameters of the Illustrative Example

Component	η	β	Other values
A	15	2	TNOW =0
B	20	3	T = 200 time unit
C	15	3	C_S =30,000
D	17	4	C_D =5,000
E	23	5	C_p=$C_{E,l}$= $C_{L,l}$=500, for all l
F	37	4	$T_{r,l}$= 5500, for all l
G	30	7	
H	22	3	
I	19	2	
J	26	4	

Experimental Evaluation

We solved the above-mentioned problem with our proposed algorithm (GHLSA) and performed a comparative study between the original case results and GHLSA results. Generated experimental penalty function data were transformed into percent deviation value (PD). We calculated the PD of objective function value resulting from proposed algorithm implementation, from the original case result using the following equation, where $\mathrm{Obj}_{\mathrm{Original}}$ represents penalty function value for original case and $\mathrm{Obj}_{\mathrm{GHLSA}}$ represents penalty function value produced using GHLSA procedure. Positive PD means the objective function value has improved (i.e., minimized) using the proposed algorithm and vice versa.

$$\text{Percentage Deviation (PD)} = \frac{\mathrm{Obj}_{\mathrm{Original}} - \mathrm{Obj}_{\mathrm{GHLSA}}}{\mathrm{Obj}_{\mathrm{Original}}} \times 100 \quad (8)$$

All calculated results for given instance for different delta values are presented in Table 2.

Sensitivity Analysis on γ

Table 2 shows that for a given instance, the proposed algorithm produced a very high objective function value which resulted in negative PD value for lower γ value (i.e., γ = 0.1 to γ = 0.3). For γ value greater than 0.3, calculated PD resulted in positive values. So for higher γ values (i.e., for γ > 0.3), the best solutions found using proposed GHLSA improved the objective function value of the original case. As γ increased, the PD value decreased for both positive and negative deviation trends. This trend was true for any γ value (Figure 6). Collected data were not very sensitive to γ value. Trend of the PD remained the same, and objective function value changed a little bit with a change in γ.

Sensitivity Analysis on δ

For all γ values, the objective function percent deviation change was logarithmic with δ (Figure 6). For lower values of δ, GHLSA produced some negative deviation. As δ increased, it generated positive deviation, as the objective function value decreased with higher δ value.

Table 2. Objective Function and PD Values for Given Instance

δ		γ=0.1	γ=0.2	γ=0.3	γ=0.4	γ=0.5	γ=0.6	γ=0.7	γ=0.8	γ=0.9	γ=1
	Original	1100101.52	1355101.52	1610101.52	1865101.52	2120101.52	2375101.52	2630101.52	2885101.52	3140101.52	3395101.52
0.1	GHLSA	-799063	-799063	-799063	-799063	-799063	-799063	-799063	-799063	-799063	-799063
	PD	-72.64	-58.97	-49.63	-42.84	-37.69	-33.64	-30.38	-27.70	-25.45	-23.54
0.2	GHLSA	-165297	-165297	-165297	-165297	-165297	-165297	-165297	-165297	-165297	-165297
	PD	-15.03	-12.20	-10.27	-8.86	-7.80	-6.96	-6.28	-5.73	-5.26	-4.87
0.3	GHLSA	-74705	-74705	-74705	-74705	-74705	-74705	-74705	-74705	-74705	-74705
	PD	-6.79	-5.51	-4.64	-4.01	-3.52	-3.15	-2.84	-2.59	-2.38	-2.20
0.4	GHLSA	61451	61451	61451	61451	61451	61451	61451	61451	61451	61451
	PD	5.59	4.53	3.82	3.29	2.90	2.59	2.34	2.13	1.96	1.81
0.5	GHLSA	119326	119326	119326	119326	119326	119326	119326	119326	119326	119326
	PD	10.85	8.81	7.41	6.40	5.63	5.02	4.54	4.14	3.80	3.51
0.6	GHLSA	186958	186958	186958	186958	186958	186958	186958	186958	186958	186958
	PD	16.99	13.80	11.61	10.02	8.82	7.87	7.11	6.48	5.95	5.51
0.7	GHLSA	172660	172660	172660	172660	172660	172660	172660	172660	172660	172660
	PD	15.69	12.74	10.72	9.26	8.14	7.27	6.56	5.98	5.50	5.09
0.8	GHLSA	226176	226176	226176	226176	226176	226176	226176	226176	226176	226176
	PD	20.56	16.69	14.05	12.13	10.67	9.52	8.60	7.84	7.20	6.66
0.9	GHLSA	226176	226176	226176	226176	226176	226176	226176	226176	226176	226176
	PD	20.56	16.69	14.05	12.13	10.67	9.52	8.60	7.84	7.20	6.66
1	GHLSA	226176	226176	226176	226176	226176	226176	226176	226176	226176	226176
	PD	20.56	16.69	14.05	12.13	10.67	9.52	8.60	7.84	7.20	6.66

Comparative Study

We performed a comparative study of the original case and the GHLSA-based results by generating different instances by changing given value of C_s, C_D,and C_P.

Sensitivity Analysis on Setup Penalty C_s

Produced results for the original case and the GHLSA case for different generated instances for six different setup costs are presented in Table 3. The presented values are the calculated PD values for the best objective function value found using the proposed GHLSA for each instance.

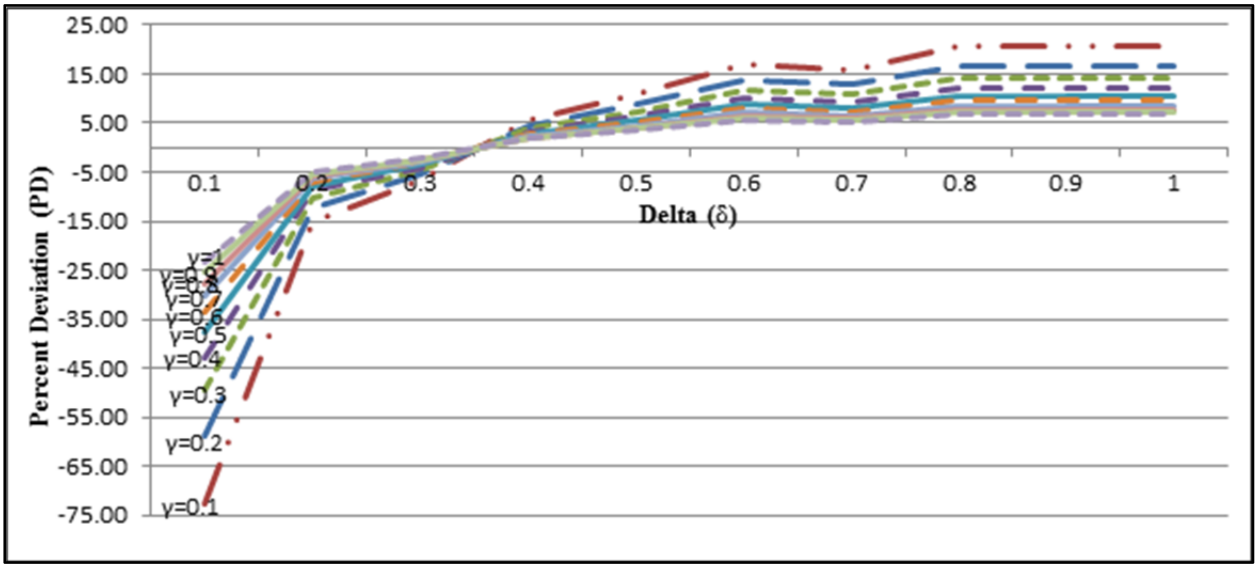

Figure 6. Change in PD Value With Delta

For all generated 60 instances, GHLSAs were able to improve (i.e., positive PD values) the original case penalty function value (Table 3). Improvement ranged from 1.08% to 20.56% in minimizing the objective function value compared to the original case. For a given C_s, penalty function value increased as γ decreased. It showed an increasing trend in PD value with increasing C_s, for any given γ. It shows the potential of this research algorithm for multi-component system maintenance where setup cost is comparatively high.

Table 3. PD Values for Different Setup Costs

Setup	γ=0.1	γ=0.2	γ=0.3	γ=0.4	γ=0.5	γ=0.6	γ=0.7	γ=0.8	γ=0.9	γ=1
30k	20.56	16.69	14.05	12.13	10.67	9.52	8.60	7.84	7.20	6.66
25k	18.07	14.32	11.86	10.12	8.83	7.83	7.03	6.38	5.84	5.39
20k	14.84	11.42	9.28	7.81	6.75	5.94	5.30	4.79	4.37	4.01
15k	10.51	7.77	6.17	5.11	4.37	3.81	3.38	3.03	2.75	2.52
10k	6.39	4.49	3.46	2.81	2.37	2.05	1.80	1.61	1.45	1.33
5k	6.32	4.12	3.05	2.42	2.01	1.72	1.50	1.33	1.19	1.08

Sensitivity on Downtime Penalty C_D

We generated 100 instances for 10 different C_D values ranging from 1k to 10k. The calculated PD values are representative of the best solution found using proposed GHLSA at granularity level 0.1 (Table 4). The proposed GHLSAs were able to improve the PD

values of all 100 instances for different C_D. PD values ranged from 3.80 to 25.24. For all γ, PD value decreased with higher C_D.

Table 4. PD Values for Different Downtime Costs

Downtime Cost	γ=0.1	γ=0.2	γ=0.3	γ=0.4	γ=0.5	γ=0.6	γ=0.7	γ=0.8	γ=0.9	γ=1
1k	25.24	23.88	22.66	21.56	20.56	19.65	18.82	18.05	17.34	16.69
2k	23.88	21.56	19.65	18.05	16.69	15.52	14.51	13.62	12.83	12.13
3k	22.66	19.65	17.34	15.52	14.05	12.83	11.80	10.93	10.18	9.52
4k	21.56	18.05	15.52	13.62	12.13	10.93	9.95	9.13	8.44	7.84
5k	20.56	16.69	14.05	12.13	10.67	9.52	8.60	7.84	7.20	6.66
6k	19.65	15.52	12.83	10.93	9.52	8.44	7.57	6.87	6.28	5.79
7k	18.82	14.51	11.80	9.95	8.60	7.57	6.76	6.11	5.57	5.12
8k	18.05	13.62	10.93	9.13	7.84	6.87	6.11	5.50	5.01	4.59
9k	17.34	12.83	10.18	8.44	7.20	6.28	5.57	5.01	4.55	4.16
10k	16.69	12.13	9.52	7.84	6.66	5.79	5.12	4.59	4.16	3.80

Sensitivity on Deviation Penalty C_P

Different C_P values, ranging from 100 to 1,000, were used to generate 100 experimental instances. All calculated PD values of the original case and the GHLSA case are in Table 5.

Table 5. PD Values for Different Deviation Penalty Values

Deviation Penalty	γ=0.1	γ=0.2	γ=0.3	γ=0.4	γ=0.5	γ=0.6	γ=0.7	γ=0.8	γ=0.9	γ=1
100	27.85	22.30	18.59	15.94	13.95	12.41	11.17	10.15	9.31	8.59
200	25.93	20.84	17.42	14.96	13.11	11.67	10.51	9.56	8.77	8.10
300	24.08	19.41	16.27	14.00	12.28	10.94	9.86	8.98	8.24	7.62
400	22.29	18.03	15.14	13.05	11.47	10.23	9.23	8.41	7.72	7.14
500	20.56	16.69	14.05	12.13	10.67	9.52	8.60	7.84	7.20	6.66
600	18.89	15.39	12.98	11.22	9.88	8.83	7.98	7.28	6.69	6.19
700	17.28	14.12	11.93	10.33	9.11	8.15	7.37	6.73	6.19	5.73
800	15.72	12.88	10.91	9.46	8.35	7.48	6.77	6.18	5.69	5.27
900	14.42	11.85	10.06	8.74	7.72	6.92	6.27	5.73	5.27	4.89
1000	12.75	10.51	8.93	7.77	6.88	6.17	5.59	5.11	4.71	4.37

In all experimental instances for deviation penalty C_P, our presented GHLSAs were successfully able to minimize the penalty function value. For all 100 instances, the found PD values were positive, which means improvement of the objective function value compared to the original case study. For different C_P values, the resulting PD values ranged from 4.37 to 27.85. PD value decreased with higher C_P for all γ (see Table 5).

Optimal δ Value

Tables 6 and 7 present the optimal δ values at granularity level 0.1, for generated instances for C_S and C_P. Note that optimal δ values for downtime instances were not

reported in the tables. For all 100 instances for C_D, the generated optimal delta value was 0.8–1.0 at granularity level 0.1. For setup cost, all instances for cost ranging from 15k to 30k, optimal δ was 0.8–1.0. For 10k setup cost instances, the optimal delta value was 1.0, and it decreased to 0.5 for the lowest setup cost 5k.

Table 6. Optimal δ Values for Different Setup Cost Instances

SetupCost	γ=0.1	γ=0.2	γ=0.3	γ=0.4	γ=0.5	γ=0.6	γ=0.7	γ=0.8	γ=0.9	γ=1
5k	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
10k	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
15k–30k	0.8–1.0	0.8–1.0	0.8–1.0	0.8–1.0	0.8–1.0	0.8–1.0	0.8–1.0	0.8–1.0	0.8–1.0	0.8–1.0

Table 7. Optimal δ Values for Different Deviation Penalty Cost Instances

DeviationPenalty	γ=0.1	γ=0.2	γ=0.3	γ=0.4	γ=0.5	γ=0.6	γ=0.7	γ=0.8	γ=0.9	γ=1
100–800	0.8–1.0	0.8–1.0	0.8–1.0	0.8–1.0	0.8–1.0	0.8–1.0	0.8–1.0	0.8–1.0	0.8–1.0	0.8–1.0
900	0.7–1.0	0.7–1.0	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
1000	0.8–1.0	0.8–1.0	0.8–1.0	0.8–1.0	0.8–1.0	0.8–1.0	0.8–1.0	0.8–1.0	0.8–1.0	0.8–1.0

For deviation penalty instances, this optimal δ value was constant for all values of C_P, except 900. For C_P = 900, for lower γ values (i.e., γ = 0.1–0.2), the δ value for best found results was 0.7–1.0 and for the rest of γ values, it was 0.7. According to the PD analysis, δ is a significant factor in finding a good solution by implementing this greedy heuristic–based methodology. The experimental results of the presented 260 instances shows that a higher value of δ, at granularity level 0.1, is a safer choice when the penalty function for all the δ values cannot be evaluated. In those cases, our recommended δ value would be 0.5–1.0, at granularity level 0.1.

Tuning Parameter δ

The presented results were very sensitive to δ. Tuning of this granularity parameter depends on the system configuration (i.e., the number of components) and available computation power. If possible, the initial tuning can be done at granularity level 0.1. Granularity level 0.1 means to change the scope of granularity δ value by 0.1. With a granularity level of 0.1, in 10 runs the algorithm would generate the best solution possible with the proposed method. If the granularity level needs to be smoother, that depends on the input instance (i.e., the input values of $T_{m,l}^k$). If $T_{m,l}^k$ values result in a very small T_{max}, then a higher granularity level may not produce any better result, as a number of components repair times may remain the same for resulting construction phase time-span T_c.

Concluding Remarks and Future Work

In this paper, we proposed a greedy heuristic local search algorithm for multi-component preventive maintenance scheduling problems. This scheduling algorithm is based on some greedy heuristics and a local search method. This new algorithm has proven to make significant improvement of the objective function criterion, compared to presented original case results. We have implemented the presented GHLSA for 260 generated

instances and found remarkable results. Deviation analysis showed significant improvement of the objective function value for all 260 problem instances. The presented greedy heuristics–based algorithm looks very promising in solving some real life preventive maintenance scheduling problems.

Future work includes the addition of another objective to the algorithm: the effect on system reliability at iteration *j*. Currently, only a cost parameter is considered when determining the earliness or tardiness of a particular component maintenance operation when coordinating system maintenance. However, it is hypothesized that a system reliability objective may change the maintenance schedule, particularly when the system schedule suggests that some components be maintained after their recommended maintenance times (tardiness), potentially resulting in an undesired system reliability.

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An Internal, Demand-Side Approach Toward Implementing Strategic Sourcing: Political, Legal, and Economic Considerations

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Abstract

A commonly cited criticism of the DoD is inefficiency in its acquisition process that leads to a high potential for waste. The purpose of this study is to explore whether the DoD's institutional setting and related bureaucratic structure prohibit leaders and policymakers from effectively implementing private sector best practices related to strategic sourcing, especially demand management. Demand management requires an organizational mindset supporting the governance of production and consumption within a commodity group. A qualitative, case study research methodology was used to explore whether the DoD's institutional framework permitted the utilization of strategic sourcing processes, such as demand management. Gortner, Mahler, and Nicholson's theoretical framework and related argument that public and private sector organizations differ from each other according to three distinct mediums (legal, economic, and political) was applied. Interview data and document artifacts were fractured and coded, then grouped into categories using a modified grounded theory strategy. Key findings suggest that the DoD's current acquisition structure permits a limited application of demand management and the private sector's key success factors given certain political, legal, and economic modifications.

Research Questions

Despite the many urgings and initiatives for improved acquisition processes and methods, the DoD continually fails to implement acquisition reform measures that would produce the desired change. Specifically, the DoD and its bureaucratic aversion to change is unable to adopt commercial best practices. Regarding its acquisition of commercial goods and services, the private sector best practice of strategic sourcing remains absent from the DoD's standardized acquisition practices despite the fact that the Office of Management and Budget (OMB) mandated its use in May 2005. As such, inefficient and tactical acquisition processes continue to produce wasteful spending practices. This problem negatively influences the American taxpayer, the DoD, and the customers that it supports, most notably the warfighter.

A possible cause of this problem is the outdated structure of the DoD's acquisition system and the procurement function's limited, administrative role in the overall acquisition process. This study investigates commercial best practices, such as strategic sourcing, and the government's limited success in applying them could assist in remedying this problem.

The purpose of this study is to explore whether the DoD's institutional setting and related bureaucratic structure has prohibited it from effectively implementing strategic sourcing practices. This study applies the theory and research asserted by Chubb and Moe (1990) to determine whether the findings—that the institution itself and its outdated bureaucratic processes are the root causes of inadequate performance—also apply to the DoD acquisition system.

In order to pursue why the DoD is unable to implement strategic sourcing practices across its acquisition platform, we propose the following three research questions:

1. To what extent does the DoD acquisition structure limit its ability to practice strategic sourcing?
2. Given certain DoD initiatives, what variables/modifications were instituted that promoted successful strategic sourcing practices?
3. Is it possible to mirror these successful examples and apply them on an enterprise-wide basis across the DoD acquisition platform?

Literature Review

To appreciate the magnitude of the study's research questions, it is first necessary to analyze and detail seminal literature that focuses on bureaucracies and organizational theories, as well as some of the key differences among the public and private sectors as they pertain to these constructs. These two overarching themes each play a significant role in determining whether public sector agencies and departments are successful, or whether they possess the potential to be successful, in adopting private sector practices.

Following this analysis and prior to exploring strategic sourcing articles from academic journals, a thorough examination of successful strategic sourcing practitioners offers insight into lessons learned, critical success factors, and other related details. This portion of the literature review highlights which strategic sourcing practices, traits, and components have proven to work and which may or may not be transferable from the private to the public sector.

Classical Literature

Theorist Herbert Simon (1997) eloquently detailed the importance of organizations in his landmark work *Administrative Behavior*:

> Organization is important, first, because it provides the environments that mold and develop personal qualities and habits. Organization is important, second, because it provides those in responsible positions with the means for exercising authority and influence over others. Organization is important, third, because, by structuring communications, it determines that environments of information in which decisions are taken. We cannot understand the inputs or outputs of executives without understanding the organizations in which they work. Their behavior and its effects on others are functions of their organizational situations. (p. 18)

Despite the increasing literature and focus on how bureaucracies are changing, traditional bureaucracies continue to run the federal government and, as such, they should be analyzed and studied to measure their impact on government operations. Assuming that

Simon's (1997) theory that organizations affect the inputs and outputs of those who work within them, ignoring organizations makes any study focusing on government processes and initiatives incomplete.

Simon (1997) asserted a clear distinction between administrators and the economic man. Administrators, according to Simon (1997), *satisfice* rather than maximize, implying that they can make decisions without knowing or ascertaining all the facts (p. 119). Simon supported this theory with decades of management and human behavior observation and research. If one were to accept Simon's assertion that administrators act in a satisficing manner, then administrators can and will make decisions with established rules. Simon (1997) characterized these rules as "relatively simple rules of thumb that do not make impossible demands upon their capacity for thought" (p. 119). Perhaps this characterization best explains the myriad of rules that Wilson (1989) detailed at length that continue to run the American bureaucracy.

Many of the bureaucratic tenants detailed by Weber (1922) and Wilson (1989) continue to dictate the composition and character of modern bureaucracies, including the DoD, which remains the largest department within the executive branch in both budget and population. Academics and practitioners alike have challenged the usefulness and efficiency of traditional bureaucracies over the past century, and these critiques and suggestions warrant consideration in view of the changing demands and expectations placed upon these organizational entities.

Although the claim that Weber (1922) is the founder of bureaucracy lies outside the scope of this research project, it is safe to label him as the first known academic to define bureaucracy's attributes and promote their use. Andreski (1984) asserted that Weber was the first to recognize the inevitable bureaucratization of modern governments and nation states, which is one of the most significant predictions in the field of public administration. Weber (1922) outlined the basic characteristics of a bureaucracy, focusing on strict and ordered rules, hierarchy among employees, written documents that guide the management of the modern office, managers who were recognized experts, and office management who followed general rules, which can be learned (pp. 50–51).

Bureaucracy and rules complement one another. Typical connotations of bureaucracies initially generate images regarding rules and regulations, a concept that Weber (1922), and nearly all theorists who touch on bureaucracy, detailed at length. Wilson (1989) asserted, "The United States relies on rules to control the exercise of judgment to a greater extent than any other industrialized democracy" (p. 342).

The DoD, perhaps more than any other executive department in the United States federal system due to its size and complexity, contains a seemingly infinite set of rules and regulations. For example, the rules that guide the DoD procurement processes are divided into several layers, including the federal acquisition regulations; the DoD FAR supplement; the DoD procedures, guidance, and information; as well as a host of local agency procedures, policies, and regulations. As of July 1, 2010, the FAR and DFARS alone are 2,074 and 954 pages, respectively. These exhaustive, overlapping rules do not include the procurement and acquisition rules put forth by the OMB in the form of directives, policy memos, and circulars, for example. A contracting officer (CO) in the DoD requires several years of both training and on-the-job experience to grasp these rules well enough to be granted a warrant that permits an officer's actions independent of a supervisor. That said, all CO actions over a certain dollar threshold, which vary depending on the action as well as the agency, must still go through a legal review to ensure the proper application of these inherently complicated regulations, further illustrating the multitude of rules and regulations

employed in running the DoD. Although industry has its own review processes, it typically falls far short of the lengthy, bureaucratic process imbedded in DoD agencies.

Regarding the topic of rules and the order that they produce, Weber (1922) focused on three primary tenants: First, regular activities are fixed in such a manner to be labeled as official duties. Second, the authority to give commands is strictly outlined and followed (Weber, 1922, p. 50). Third, only those with the qualifications and authority are employed and are done so in a continuous manner. Whether these primary characteristics of how rules are implemented and sustained remain valid in today's environment warrants serious debate; however, regardless of one's opinion on this particular topic, the fact remains that some degree of these characteristics is evident in today's DoD.

Osborne and Gaebler (1992) focused several publications in the early 1990s on public- and private sector differences in an effort to highlight the need for change and, more broadly, for the public sector to begin adopting private sector practices and processes. Osborne and Gaebler (1992) in *Reinventing of America* stated, "We embrace our rules and red tape to prevent bad things from happening, of course. But those same rules prevent good things from happening. They slow government to a snail's pace" (p. 111). There are certainly official duties in the DoD, and the authority to perform and authorize certain actions are clearly spelled out in a host of policies and regulations. These actions and authorizations are limited to those officials who are granted explicit authority to act on behalf of the DoD. Focusing on the topic of defense acquisition as an example, each defense agency has its own set of rules and policy memorandums that carefully and explicitly outline the authority levels of certain employees and their respective positions. At a higher level, each defense agency and each of the defense services must follow the highly integrated DoD Instruction 5000.02, which is the lengthy guide that details the multitude of approvals, documents, and authority levels that serve to uniformly control the acquisition of major defense acquisition programs. In short, Weber's (1922) intense focus on the rigidity of rules within a bureaucracy is a characteristic that continues to flourish in the DoD.

Wilson (1989), citing Weber as well as his own experiences, supplemented these thoughts on rules with his own assessment regarding the gains and losses produced by the rigid application of rules that Weber promoted. Wilson (1989) asserted that the difficulty lies in

> striking a reasonable balance between rules and discretion is an age-old problem for which there is no 'objective' solution …. At best we can sensitize ourselves to the gains and losses associated with the governance by rule rather than by discretion. (p. 342)

In the world of defense acquisition, the line between rules and discretion is anything but concrete. For example, nearly all the rules have exemptions specifying that government officials can employ their own discretion. However, the constantly changing political realities and pressures frequently determine the practitioner's ability to use such exemptions and related discretion.

Demand-Side Management

Demand-side management involves the use of financial incentives, market mechanisms, education, efficiency measures, or other programs to modify the demand for a product or service (Strengers, 2011). The demand management process attempts to identify specific sources of demand so that procurement organizations can ameliorate the risks associated with sources of demand. Demand management attempts to control when or where demand occurs in order to match it efficiently with available capacity and smooth highs and lows of demand into a more consistent requirement level (Jack & Powers, 2009).

In the DoD, demand often expands to the level of funding allotted for a supply or service. So rather than demand driving funding and procurement, funding drives demand.

Jack and Powers (2009) identified examples that might occur in the health care industry, such as an aging and growing population, the increase in some diseases while others are reduced, demand for new treatments and therapies, insurance allowances for procedures, and the prevalence of managed care.

As we identified previously, organizations are impacted by politics and individual limitations are commonplace. In these circumstances, individuals have differences in preferences as a result of their value systems and bounded rationality. These different preferences impact the sourcing of products and services (Cox, Chicksand, & Ireland, 2005). These differences also serve as major sources of resistance to the adoption of enterprise-wide sourcing strategies.

Public and Private Sector Organizational Structures: A Comparative Analysis

Although organizational theory, similar to studies on management, generally does not differentiate between the public and private sectors, there are common characteristics, traits, and features. The subtle differences that do exist can and do have profound consequences when attempting to implement similar processes and practices. Academics Gortner, Mahler, and Nicholson (1989) clarified this point and published a comprehensive text that focused on the uniqueness of organizational theory as it applies to the public sector. Although these authors admit that the lines that once separated the sectors have somewhat blurred due to increasing public sector laws that uniformly apply to both sectors, as well as outsourcing, the public sector's push toward commercial practices, and so on, they still convincingly argued that the public sector demands its own focus on organizational theory.

Gortner et al. (1989) asserted three fundamental components that separate public agencies from their private counterparts: legal, economic, and political nature and roles. These authors argued that public and private organizations differ "in this most profound way: *It is the business of public bureaus to administer the law*. … Compliance with private rules and regulations is voluntary: Non-compliance in the public sphere may result in coercion or force" (pp. 19–23).

In their landmark essay "Comparing Public and Private Organizations," Rainey, Backoff, and Levine (1976) mirrored the thoughts above regarding the unique legal differences between the private and public sectors and the impact that these differences creates. Regarding the constraints of the legal system that applies to the public sector, Rainey et al. (1976) claimed that these constraints limit the public manager's choices as to both entry and withdrawal of certain undertakings (p. 238). In short, the legal environment that guides the public sector frequently undermines its ability to freely choose its undertakings and related practices and processes, a fact that is rarely noted or appreciated by the public it serves.

The economic differences between the public and private sectors can be succinctly summarized by the fact that a private entity is largely motivated by profit whereas a public agency must blend efficiency with political and legal concerns, and mandates, some of which were discussed previously. For example, many of the political embargoes and trade restrictions placed by the United States were instituted due to political concerns, not to enhance profitability.

Although private entities do not operate in a vacuum, they certainly avoid the type of interference and political pressure noted by Gortner et al. (1989). Allison's (1979) landmark

presentation comparing the sectors and highlighting their fundamental differences specifically noted this point. Allison (1979) asserted, “Government managers tend to have relatively short time horizons dictated by political necessities and the political calendar” (p. 29). Allison’s point adds complexity to the position of a public administrator, who must balance political demands within narrow timeframes, a dangerous combination that inevitably creates hurried and frequently inefficient processes. An examination of the practitioner literature will illustrate the key success factors (KSFs) that are inherent in any strategic sourcing program.

Practitioner Literature: Key Success Factors

The overlapping themes regarding what practitioners claimed were necessary ingredients for successful strategic sourcing implementation and what academia is discovering through research are plentiful. We identified a host of repeating suggestions and criteria for a successful strategic sourcing program emerged from the literature. These criteria, or key success factors, can be categorized into the following high-level headings: the overall status of the purchasing function, effective leadership within the organization, the ability of strategic sourcing teams to cross functional areas, and working jointly with suppliers in an integrated fashion in contrast to establishing an arms-length relationship. This final KSF includes developing suppliers in addition to simply working together. The following analysis synthesizes the existing literature’s contribution to these KSFs.

Status of the Purchasing Function

As mentioned by Baldwin et al. (2000), Moore et al. (2002), Laseter (1998), and others, practitioners have publicized the need for purchasing to cease its stereotypical role of serving as an administrative or clerical function. Driedonks, Gevers, and van Weele (2010) stressed this point in their study regarding how to manage the effectiveness of strategic sourcing teams when they asserted, “Although things have changed dramatically over the last decades, the purchasing profession has a history as a clerical function” (p. 109). Driedonks et al. (2010) claimed that the ability of strategic sourcing to create a competitive advantage is what has largely raised the prominence of the purchasing function (p. 109).

Because the DoD has not altered the status of its purchasing function since it attempted to implement strategic sourcing in May 2005, perhaps because it does not have to compete in the marketplace and establish any type of competitive advantage, it would not satisfy this KSF. Johnson (2005), whose memorandum implemented government-wide strategic sourcing in the federal sector, did not establish any type of strategic sourcing organizational structure or make any mention of acquisition process and procedures. In short, Johnson’s OMB memorandum mandated a commercial best practice but maintained the status quo in terms of the existing status and role of the purchasing function.

Kocabasoglu and Suresh (2006) enhanced the notion of increasing the status of purchasing when they asserted that successful strategic sourcing implementation depends on purchasing and supply managers partaking in the organization’s strategic processes (p. 7). The typical DoD framework—whereby requirements are generated and provided to the purchasing function to simply administer an order—falls far shy of the type of strategic, organizational integration that Kocabasoglu and Suresh label as a KSF. Schneider (2011), a professor of contract management at the Defense Acquisition University (DAU), asserted the following thoughts regarding the status of the purchasing function within the DoD:

> We may teach the acquisition lifecycle and use of Integrated Product Teams but the reality is that in many DOD organizations, procurement is not engaged until far too late in the acquisition planning process. This means the

value add of the business advisor is minimized and it is no surprise that contracting is seen as more of an administrative paper-pushing function. (Personal communication, March 28, 2011)

Ogden, Rossetti, and Hendrick (2007) confirmed the importance of this KSF, offering that the purchasing literature has identified “status within the organization” as one of the key determinants of purchasing’s strategic influence (p. 4). The DoD’s failure to break through the bureaucratic, stove-piped nature of its acquisition system and purchasing’s continued administrative role will inevitably add to the challenge of implementing strategic sourcing initiatives and practices.

Effective Leadership

Wisma, Schmidt, and Naimi (2006) asserted that significant resources need to be focused on leadership in order to properly manage the inevitable change that accompanies a strategic sourcing initiative (p. 174). Wisma et al. (2006) argued that such an initiative without an effective leader to manage the significant change that stems from executing strategic sourcing practices will surely lead to failure. Although Johnson’s (2005) OMB memorandum directed agencies to implement strategic sourcing was addressed to senior leaders within the executive departments—the chief acquisition officers, chief information officers, and chief financial officers—there was no guidance on how to lead the inevitable change that this initiative would create. Further, the leaders who received this OMB tasking were to do so in a minor, part-time capacity, further emphasizing the weakened approach employed by the OMB in instituting this commercial best practice.

By comparison, the private sector typically hires experts with leadership skills whose sole focus is to drive successful strategic sourcing initiatives. In reviewing the organizational structures and leadership roles of private sector firms that have experienced successful strategic sourcing programs, it turns out that their leaders are focused on the primary mission of ensuring that their programs exceed the established goals and metrics. Klein (2004) included this approach as one of the three key steps to excellence. Klein (2004) cited Prudential as a best-in-class case study in his research and stated how its strategic contracts manager led the needed change (p. 24). This senior-level executive focused on driving effective strategic sourcing practices in the company. This type of focus is not only lacking but is frequently altogether absent in the DoD environment.

The federal government’s approach was to add this challenging initiative to the countless other duties assigned to their senior leaders, and to do so with a flat-lined budget. In this instance, the federal government reverted to the hierarchical structure and tasked the senior-most leaders who delegated down to their subordinates in hopes of some level of progress (Johnson, 2005). Referencing Simon’s (1997) thoughts, the outputs of executives cannot be understood without understanding the organizations in which they work (p. 18). Regarding the implementation of strategic sourcing in the federal sector, the important trait of leadership was handled in the bureaucratic fashion by tasking and delegating in lieu of the commercial approach of hiring dedicated leadership to ensure that the proper level of focus and energy supported the initiative (Johnson, 2005). It is not a failure of leadership but an organizational failure that best explains the outputs of the federal and, more specifically, the DoD leaders. This possibility should be kept in mind moving forward.

Leadership’s impact on strategic sourcing has been studied, albeit only with private sector data. Hult, Ferrell, and Schul (1998) examined the impact of leadership on a set of individual purchase outcomes related to the sourcing process. Hult et al. (1998) studied leadership’s impact on an organization’s purchasing cycle times and relationship commitments, both critical measurement’s in assessing an organization’s success in a

strategic sourcing environment. Although Hult et al. (1998) divided leadership into multiple categories, the underlying hypothesis that leadership impacts purchasing outcomes was confirmed in their study.

This is not to imply that effective leadership alone ensures that strategic sourcing initiatives experience success. For example, when Hawkins, Randall, and Wittmann (2009) researched factors contributing to the use of reverse auctions, a tool frequently used by strategic sourcing teams, they illustrated that leadership was not a contributing factor. Hawkins et al. (2009) revealed that leadership in their study only proved to be marginally significant and negatively related to the use of reverse auctions (p. 65). Although still marginally effective and considered by most to be a critical part of successful strategic sourcing practices, leadership alone does not guarantee positive outcomes from a strategic sourcing perspective.

Cross-Functional Representation

The internal coordination of purchasing with other functions is a KSF that relies heavily on internal communications. Freytag and Mikkelsen (2007) stressed the importance of this KSF, stating that the managerial challenge of managing relationships is critical in implementing strategic sourcing. Freytag and Mikkelsen (2007) asserted, “The key to success is that all parts of an organization cooperate, and that no part of the organization passively or actively shows a reluctant attitude to handling the tasks” (p. 189). Internal communication and managing relationships across the DoD’s vast, stove-piped acquisition system is difficult to effectively execute.

Acquisition is comprised of a handful of job series, although this handful varies from agency to agency. These job series, ranging from contracting officers to program managers to engineers to logisticians, contain their own training, competencies, and skill sets that rarely overlap, thereby exacerbating the limited view and scope of a DoD acquisition official (Defense Acquisition University [DAU], 2010). For example, DAU is responsible for teaching certification courses to the DoD acquisition workforce. The DAU website (2011a) put forward the following clarification: “The Defense Acquisition Workforce Improvement Act required the Department of Defense to establish a process through which persons in the acquisition workforce would be recognized as having achieved professional status” (para. 1).

Each DAU campus is divided up into six departments: contract management, logistics, program management, systems engineering, business, cost, and finance (DAU, 2010). The certification courses provided by the DAU rarely overlap, and the instructors employed to teach them typically teach only within their limited area of expertise. This approach serves only to heighten the stove-piped nature of the DoD acquisition system, making the internal coordination of purchasing with other functions altogether impossible.

Mookherjee (2008) studied the criticality of moving toward a flatter organization as opposed to traditional vertical organizations that typically define government bureaucracies if an organization is to effectively practice strategic sourcing. Mookherjee asserted that companies are therefore moving, and sometimes being forced, away from the classical, vertical structures toward those that are more flexible (p. 72). The current DoD organizational structure and its stove-piped nature violate the tenants of flexibility and horizontal platforms that Mookherjee’s research endorsed.

In a study similar to Mookherje’s (2008) study, Gopal, Viniak, and Caltagirone (2004) outlined a model to achieve a strategic sourcing that relies heavily on the effective use of cross-functional teams. Gopal et al. (2004) asserted, “The project’s success depends heavily on the team’s formation. Purchasing, logistics, operations, engineering, and finance all need to be represented on the team” (p. 56). Again, considering that the DoD currently

hires, trains, and works according to functional area, each particular function is frequently ignorant regarding the roles and responsibilities of their counterparts in the other functional areas.

Mills (2010), a former program manager in defense-related acquisition and current DAU professor of program management, recently asserted the following list of barriers that limit the DoD's ability to form integrated product teams: lack of empowerment, unclear goals, poor leadership, unreasonable schedule, insufficient resources, and lack of commitment (p. 31). This translates the tasking of a joint cross-functional team into a monumental challenge, at least for the DoD bureaucracy.

This is not to imply that the DoD has not long been warned regarding the need to shift from a functional, narrow focus toward the industry standard of cross-functional teams. For example, Dupray (2005), a contracting officer for the U.S. Navy, detailed the need to transform the DoD's stove-piped approach to acquisition and move from a functional approach toward a joint, strategic approach (p. 8). Despite the OMB policy letters, countless executive reports, and supporting literature from the private sector, the massive bureaucracy that is the DoD requires fundamental, organizational change to truly shift from its existing, single functional area focus, which unfortunately prohibits, or at least limits, strategic sourcing processes.

Buyer–Supplier Relationships

Information sharing and the development of key suppliers are two of Kocabasoglu and Suresh's (2006) KSFs that come close to violating the ethical standards and statutory regulations that guide the federal sector's acquisition system. The DoD acquisition system, from a purchasing perspective, is guided by the federal acquisition regulations, which place the concepts of fairness and competition above these KSFs, regardless of their importance in executing strategic acquisition practices. For example, FAR 3.101-1 offered the following guidance:

> Government business shall be conducted in a manner above reproach and, except as authorized by statute or regulation, with complete impartiality and with preferential treatment for none. Transactions relating to the expenditure of public funds require the highest degree of public trust and an impeccable standard of conduct. The general rule is to avoid strictly any conflict of interest or even the appearance of a conflict of interest in Government-contractor relationships. (General Services Administration [GSA], 2011, section 3)

It is easy to decipher why contracting officers are hesitant to establish long-term relationships with suppliers because the FAR clearly articulates that complete impartiality shall guide the DoD acquisition process.

The current bureaucratic structure of the DoD and the lengthy list of regulations that guide it prohibit certain buyer–supplier relationships that serve as common practices in the private sector (GSA, 2011). For example, FAR 15 details how contracting officers are to treat all competing industry partners fairly to ensure equity and justice in the federal contracting process. FAR 15.306(e) specifically stated, "Limits on exchanges. Government personnel involved in the acquisition shall not engage in conduct that favors one offeror over another" (GSA, 2011). When these rules are violated, the losing contractor in a competitive process has the legal right to protest the government's decision.

FAR 33, which covers protests, disputes, and appeals, is dedicated to outlining the processes and procedures afforded to contractors for submitting protests when it suspects

that the government violated the regulations. For example, Northeast Military Sales (NEMS) protested the Defense Commissary Agency's decision to award to another, competing firm. NEMS won the protest and the Defense Commissary Agency had to restart its entire acquisition process because it failed to properly follow the rules regarding the engagement of industry suppliers. In its ruling, the GAO (2011) asserted, "NEMS broadly challenges the agency's technical, past performance, and price evaluations, as well as the adequacy of discussions. We sustain the protest" ("Decision" section, para. 1). The reference to discussions in the GAO decision highlights the government's continued failure to properly engage with industry. This recent case illustrates the complexity involved regarding the DoD's use of this particular KSF.

In line with KSFs that promote successful strategic sourcing implementation, Towers and Song (2010) provided that long-term purchasing arrangements are necessary between buyer and supplier to ensure a strategic relationship that will lead to effective strategic sourcing practices (p. 542). There are a host of bureaucratic hurdles that make this KSF difficult to achieve, including the budgetary system that funds DoD acquisitions, the restrictions regarding the use of multiyear funds, the current administration's intense focus on increasing competition, and so on. For example, the DoD uses various categories of money to fund its acquisitions, all of which have strict time limits regarding when they can be obligated and the purpose that they are used. Operations and maintenance money, for example, must be used within the year that it is provided or it expires. Further, it can only fund contracts for a period of 12 months, further emphasizing the point regarding the difficulty for the DoD to establish long-term relationships with suppliers.

To illustrate the complexity regarding the DoD's ability to establish long-term relationships with suppliers, consider the following DoD guidelines established in the DAU's (2011b) CON 216 Legal Considerations in Contracting course: "Annual appropriations are made for a specified fiscal year and are available for new obligation only during the fiscal year for which made. Routine activities of the federal government are, for the most part, financed by annual appropriations" (p. 206). It is obvious from the literature that the long-term relationships promoted by strategic sourcing experts far exceed the one-year time limit that is typically established in the Appropriation and Authorization Acts.

In the summary of their study, Chan and Chin (2007) claimed that managing and collaborating with suppliers early in the process offers companies a competitive advantage (p. 1407). This competitive advantage escapes the largest buying entity in the world because of its bureaucratic rules that continue to prohibit it from applying commercial best practices.

Although strategic sourcing has yielded enormous savings for industry over the past 20 years, the majority of strategies focus on the interactions with suppliers through contract award. The management of the strategy in the post-award phase has had comparatively little attention paid to it. This is a reflection of contracting's perceive administrative role (Hughes & Wadd, 2012).

KSFs Summary

The four KSFs detailed in the previous sections are all limited when considering the existing institutional structure that guides the DoD acquisition system. Although both scholars and practitioners may argue over which KSF is most critical to an organization that is implementing or practicing strategic sourcing, the overlapping themes were constant. Thawiwinyu and Laptaned (2009) executed a detailed study on the impacts of strategic sourcing on supply chain performance management. In their literature review, they asserted the following as the main elements of strategic sourcing: strategic elevation of the

purchasing function, internal coordination between supplier and purchasing, long-term relationships with suppliers, and supplier involvement in planning and design. Their assessment assists in validating the fact that these elements or KSFs are constant and need to be massaged into the DoD institutional setting if the DoD expects to realize the utilization of strategic sourcing processes.

Thawiwinyu and Laptaned (2009) asserted, “Firms that implement strategic sourcing experience significant improvement in their supply chain performance management, specifically in terms of responsiveness and satisfaction of customer” (p. 20). In an era of budget cuts, multiple war efforts, and overall economic uncertainty, the DoD should focus its efforts mightily on how to properly implement strategic acquisition practices so its customers (the warfighter as well as the taxpayer) can experience increased customer satisfaction, however that might be defined (e.g., increased savings, better service, decreased delivery times, etc.). Further, the potential regarding positive social change associated with the reallocation of financial resources is tremendous serving to heighten the demand for strategic sourcing in the DoD and, more broadly, in the public sector.

Research Methods

Considering the research questions and their exploratory nature, combined with the fact that the academic literature revealed little information on strategic sourcing in the public sector, a case study methodology is the best approach for this study. Recognizing that the literature on strategic sourcing in the public sector is limited illustrates that this truly is an exploratory study. This research effort focuses on the United States Air Force and its Strategic Sourcing Program Management Office (SSPMO), referred to as the Air Force’s Enterprise Sourcing Group (ESG). To properly assess the impact of how the DoD could adjust its existing organizational structure to better promote strategic sourcing practices, a program that has illustrated progress in this realm naturally had to serve as the case study. Additionally, if the research question of whether a modified strategic sourcing program could be applied on an enterprise level within the DoD is to be explored, a program that has illustrated the ability to execute strategic sourcing within the existing regulations had to be selected. The Air Force’s SSPMO readily meets these requirements.

This study utilizes both an archival and documentation review, as well as interviews, in an effort to compile as much data as possible and to ensure a comprehensive, triangulated approach. The archival records and documentation review were analyzed by the Gortner et al. (1989) framework that characterizes public and private sector differences along three distinct mediums: legal, economic, and political (see Table 1). The interviews were conducted along the private sector’s KSFs that emerged in the literature review.

Table 1. Air Force Strategic Sourcing Archival Records and Documentation Mapped to the Gortner et al. (1989) Framework Categories

Air Force archival record or documentation	Gortner et al. (1989) framework (Legal/Economic/Political)
IG5307.104-93 AF Strategic Sourcing and Commodity Council Guide (U.S. Air Force, 2010a)	Legal
Charter for the Air Force Civil Engineering Commodity Council (U.S. Air Force, 2010c)	Legal/Political
Charter for the Air Force: Air Force Medical Service Commodity Council (U.S. Air Force, 2010b)	Legal/Political
Charter for the Air Force Furnishings Commodity Council (U.S. Air Force, 2010d)	Legal/Political
Strategic Sourcing Task Group Final Report Briefing to the Defense Business Board (DBB, 2011)	Legal/Economic/Political
ESG's (2011) Strategic Alignment and Deployment Briefing to the Air Force Materiel Command	Legal/Economic/Political
ESG Strategic Sourcing Briefing to the Air Force Materiel Command (AFMC; Knipper, 2011)	Legal/Economic/Political
State of the ESG/Follow-up to AFMC/CA Briefing to the Air Force Materiel Command (Shofner, 2011)	Legal//Political
ESG Strategic Planning Charters	Legal/Economic/Political

The strength of this study lies in the fact that the methodology aligns with the research questions that are guiding it. The approach to triangulation assures that the research questions are explored and supported by a myriad of viewpoints and data sources, thereby strengthening the data and related analyses.

We conducted a rigorous case study using a single unit of analysis, the United States Air Force SSPMO, with multiple cases, which are the three commodity councils. In this case study we incorporated three data sources, and synchronized the results of the documentation and archival records analyses, executed through the Gortner et al. (1989) organizational framework, with follow-on interviews of the employees running the referenced commodity councils. This comprehensive approach to triangulation, along with the detailed steps to minimize or eliminate the validity threats, ensures that the proposed research questions are pursued with academic rigor.

Research Findings and Impact on DoD Acquisition

The archival records and documentation review clearly provides invaluable insight into this study's research questions. That portion of the study highlighted how the DoD's bureaucratic structure does not limit an agency's ability to launch a strategic sourcing program, which alone validates the usefulness and contributory nature of this research effort. The extent to which it may limit an agency's ability to successfully employ strategic sourcing practices remains somewhat less defined.

In the best of circumstances, demand managers must address a number of challenges that occur when meeting requirements including product over specification,

premature or tardy establishment of specifications, frequent changes in specification, poor or non-existent demand information, fragmentation of spend, maverick buying, agency politics, and the risk-averse nature and culture of the organization (Cox, Chicksand, & Ireland, 2005). Our findings indicate that each of these challenges is exacerbated by the DoD bureaucracy.

Product overspecification occurs when individual users are permitted to define requirements, rather than a team of experts representing the enterprise requirements. Premature establishment of specifications may limit the sourcing team's ability to negotiate a solution with suppliers, or to identify current state-of-the-art or alternative best-value solutions. Changes in specification make the organization susceptible to changes in price from suppliers that may increase total cost. Poor demand information deprives the organization of making informed decisions and puts them at a negotiating disadvantage. Spend that is dispersed to more vendors than necessary increases transaction cost; however, the political environment that DoD buyers work in requires attention with regard to small business vendors. The risk-averse nature of DoD buying organizations is exacerbated by the penalties assessed when an innovative strategy proves unsuccessful.

The ESG's ability to work around the legal, political, and economic differences to continue to push its program forward is a testament that the limitations imposed by the DoD bureaucracy can be overcome or, perhaps more appropriately, circumvented. The ESG was able to modify certain processes and regulations to work around barriers. This seemingly simple achievement highlights the greater impact of applying the ESG's approaches, processes, lessons learned, and achievements toward other DoD agencies and services. Additionally, the idea that an enterprise-wide DoD strategic sourcing program could take root is within the realm of the possible, a thought that traditional bureaucrats would likely dismiss.

The interview data illustrate that the Air Force ESG, operating under the same rigid DoD acquisition structure as its peers, was able to explore and achieve varying degrees of success with respect to the KSFs that emerged in the literature. The research results detailed in this study revealed that the ESG was able to significantly advance the status of the purchasing function as well as the concept of cross-functional representation on the strategic sourcing commodity councils. Although progress was evident in the data, this does not imply that the ESG reached a maturity level equal to its private sector peers. Some of its shortcomings (e.g., bureaucratic processes that result in inefficient reporting structures and limited number of SMEs on the commodity councils) are likely related to the organizational structure and the related limitations that this produces.

The KSFs focusing specifically on effective leadership and engaging suppliers in a collaborative manner have witnessed success to a lesser extent than the aforementioned KSFs. The limited but nonetheless noteworthy ESG successes in these specific KSFs are easier to tie to the DoD's bureaucratic structure. For example, leadership within the DoD is still focused on tactical and narrow-minded approaches that tend to focus on supporting only those initiatives that leaders either own or are at least personally invested in versus the strategic approach of supporting initiatives that benefit the organization. Similarly, the bureaucratic culture and rules surrounding fairness and competition makes the full realization of the final KSF that focuses on supplier collaboration difficult, if not impossible, to witness in the short term.

This research provides a solid baseline for both the ESG and its DoD counterparts to recognize what can be initially achieved, which KSFs are more difficult and may require additional support or changes, and which approaches, measures, and processes have

proven most effective. Although more detailed answers to these questions will only be possible over time, this study has produced significant and worthwhile information that will prove useful to the Air Force and, more broadly, the DoD as it continues to move toward more strategic sourcing and related acquisition practices.

Although the DoD acquisition structure limits its own ability to efficiently establish and promote strategic sourcing processes, it does not block it entirely. ESG employees expressed confidence in the fact that, over time, its program will mature. It has already made significant progress in two years within a bureaucratic structure that has solidified its cultural norms over the past 50 years. This encouraging thought demands additional research, especially in light of the positive social change that will naturally stem from the DoD's ability to realize effective, robust, strategic sourcing practices and programs.

This research effort has produced obvious demands for action from DoD acquisition leadership, related policy leaders, and practitioners alike (e.g., contracting officers and program executive officers). The fact that the ESG was able to effectively initiate a fully functioning strategic sourcing program management office within the boundaries of the same bureaucratic environment that guides and governs its peers mandates that other DoD agencies and Services take the initiative to implement strategic sourcing practices and reap the myriad benefits that it offers.

As a leader in this particular space, the Air Force ESG should meet with its DoD counterparts to review both its successes and failures. It should explore how its peers can and should follow in its footsteps and actively partner with them in establishing similar PMOs at their respective services and agencies. The ESG should also record a baseline for its current position and benchmark it against its goals and private sector peers to determine how much further it can advance its current progress and what it will require to do so. The ESG should map out these next steps for the critical stakeholders and leadership who can and should help it achieve its goals. In lieu of begging for additional leadership support and better cross-functional representation, the ESG should be more proactive in gaining the type of leadership and stakeholder support that will endorse these supportive measures and drive it from the top down. These types of aggressive pursuits pose potential gains that more than justify their endorsement.

Significance of This Study

The purpose of this exploratory case study research effort was to initiate an investigation into whether the DoD's bureaucratic structure limits its ability to practice strategic sourcing. The resulting data illustrate that although the structure may have a limiting effect, it certainly does not prevent implementation and potential success in a number of strategic sourcing processes and areas. The legal, environmental, and political differences between the public and private sectors did not prevent the Air Force's ESG from successfully launching its SSPMO and from achieving initial success stories. This research should ultimately prove valuable for its discoveries that strategic sourcing success is possible within the DoD, that the ESG's success is likely transferable to other DoD services and agencies, and that the KSFs required for success can be implemented and achieved, to some degree, within the DoD's bureaucratic environment.

We are pragmatic enough to stipulate that the bureaucratic and risk-adverse nature of DoD procurement will change little in the near future. As a result, the routinized tasks that are currently repeated with each transaction that procurement organizations conduct will also continue. We propose that strategic sourcing can make a significant contribution in this area by accomplishing those routinized tasks a single time for a group of products or services. Such a strategy will yield significant process cost savings for the enterprise.

Even with these discoveries, this field of research begs for additional studies and more granular, targeted focus areas. For example, the ESG must explore how to better achieve each of the four KSFs within DoD regulations if it seeks to mature its existing SSPMO. Another key area of focus for the ESG should be to better understand how to restructure its acquisition function areas in the hope of doing a better job at achieving the stated KSFs. The ESG's peers should explore and study how they can mirror the ESG's success, improve on the existing lessons learned, and team with the ESG to drive cross-agency and department collaboration.

Examining the broader topic of private sector practices within the federal sector is another area that is ripe for exploration. This strategic sourcing case study could be expanded to examine the topic of commercial best practices within the federal sector and what is (and is not) possible or, perhaps, what is (and is not) warranted or, perhaps, what is (and is not) necessary in these challenging fiscal times.

All considered, the purpose of this study was to launch the necessary investigation of how to apply efficient commercial practices within a seemingly rigid bureaucratic environment. This research is meant to initiate the larger and much more focused, follow-on research that is hopefully waiting to be explored by other scholar-practitioners in the field of public administration.

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Optimizing Causes of Procurement Cost Through Strategic Sourcing: The Impact of Rate, Process, and Demand

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Abstract

The benefits of strategic sourcing have been realized by private industry for over two decades. Despite the compelling business case presented, the adoption of strategic sourcing tenets in government procurement has been slowed by a lack of leadership and committed resources (GAO, 2012). We believe that advancing the ability to identify, capture, and communicate cost savings that accrue from strategic sourcing activities will allow government procurement leaders to better articulate the value of such programs. Enhanced communication will enable leaders to pursue the appropriate resources to sourcing teams. In order to tell the story in a more effective manner, leaders must understand the types of cost they are incurring and the drivers of cost that they can impact, and they must ensure that their teams take credit for the total spectrum of cost that they affect. This paper examines the various types of savings that may accrue to an organization pursuing strategic sourcing strategies and recommends the grouping of savings into rate, process, and demand categories. In addition to introducing the types of cost, examples of cost and scenarios whereby organizations have achieved cost savings are presented.

Introduction

Strategic sourcing offers a myriad of practices, models, and processes that are typically targeted at a specific cost driver and/or cost pool. Although strategic sourcing and its potential impact are far reaching, it consistently aims to drive efficiencies and savings across an organization. After briefly detailing some of the potential cost savings and efficiency areas across the supply chain, we will specifically hone in on an organization's

ability to affect the following cost groups: rate, process, and demand. These cost groups will be defined, explained, and supported with examples to illustrate the potential impact that sourcing strategies can have when directly applied to them. In the current fiscal climate, it is imperative that any DoD procurement strategy be supported with tangible metrics and a calculated return on investment (ROI) so that an effective business case can be made to ensure leadership support and follow-on execution. The recommended approach of applying strategic sourcing strategies targeted to achieving efficiencies in the rate, process, and demand cost groups significantly advance procurement leaders' ability to develop a compelling and comprehensive business case.

Types of Strategic Sourcing Cost Savings

The broad spectrum of cost in the supply chain includes manufacturing, administration, warehouse, distribution, capital, and installation cost (Pettersson & Segerstedt, 2012). By considering all phases of the supply chain, strategies formulated by strategic sourcing teams influence the cost drivers in each of these cost pools.

Strategic sourcing activities have the ability to impact each of these key cost areas. As we shall discuss, standardized configurations can reduce manufacturing costs. Bulk ordering can reduce distribution cost. Just-in-time delivery can reduce or eliminate warehouse cost and capital cost. Enterprise-wide contracts can reduce installation costs. Although these steps may help reduce external costs, focusing on the procurement activity itself can reduce process costs in the administration cost pool.

It is interesting that private industry organizations have dedicated tremendous effort and focus on the management of internal cost (Cokins, 2001). However, they spend much less time attempting to influence the internal behavior of vendors in their supply chain in any way other than price negotiations. To the small extent that government procurement exerts influence on supplier behavior, it is constrained to proposal and contract policy and small business regulations. In the converse of industry behavior, government spends comparatively little effort in attempting to understand and enhance their internal processes. Both industry and government can benefit from improved understanding and involvement in supplier behaviors and vendor cost drivers; and government could see tremendous value in an examination of the internal processes and cost associated with procurement.

Of course focusing on cost "numbers" is of limited value. As Cokins (2001) put it, in describing successful cost managers, "You do not really manage costs, you understand the causes of cost" (p. 28).

The recent history of cost management has utilized several different tactics. In the 1970s, direct product profitability (DPP) was utilized. This system focused on the costs associated with a particular product (Cokins, 2001). In the 1980s, total cost of ownership (TCO) emerged. TCO examined the entire cost to acquire, use, and dispose of an item, rather than just considering the purchase price (Ellram, 1994). Activity-based costing (ABC) gained popularity during this time as well. ABC places cost in categories related to organization activities or objectives (such as business development or presentation preparation, rather than aggregate categories such as labor cost). As a result, use of ABC provides insight into the cost of specific organizational activities. As is the case with most of these cost systems, ABC has an inward-looking focus (Cokins, 2001).

From a strategic sourcing perspective, leaders should be focused on both internal and external causes of cost. Further, the causes of cost of concern should be those that the strategic sourcing team can affect. We recommend classifying the causes of addressable procurement cost into three distinct cost groups that can be impacted by sourcing strategies: rate, process, and demand.

Rate

In almost every case, an organization's first efforts to implement strategic sourcing are aimed at attempts to reduce the cost paid per item for a particular good or service. These initial efforts often are of the "leveraged buying" variety. A clear example of leveraged buying is presented in the scenario wherein consumers purchase 50 rolls of paper towels in bulk at a shopping club outlet to achieve a reduced cost per item. Leveraged buying allows an organization to achieve rate cost savings. Simply put, the cost per unit paid for the same product or service is reduced by developing and implementing rate savings related strategies. Implementing leveraged buying strategies can achieve quick wins for the sourcing organization and prove particularly successful in straightforward commoditized product or service groups. However, rate savings are just one type of cost that organizations can impact through strategic sourcing.

Process

Although the savings realized through rate reductions are often finite, they are often substantially realized in the short term. The more complex buckets, process cost and demand cost, have potentially higher savings over a longer period of time. Process cost is the cost that is required for an organization to buy a product or service. This cost includes all facets of the procurement process from requirement definition through contract management and closeout. In organizations utilizing decentralized buying, similar items are purchased in small quantities at many locations on a repeated basis. The cost for each transaction is repeated with each buy. Organizations can reduce this cost by pursuing strategies that put a common buying process in place and allow purchases to be repeated at multiple locations on a recurring basis (Reed, Bowman, & Knipper, 2005).

Consider a web-based shopping service that allows customers to compare prices and load buying data and delivery information one initial time. On subsequent visits, the customer might simply select an icon to purchase the same item again, thus reducing the cost in time and personnel required to complete the transaction. In federal purchases, moving away from single transactions to utilizing pre-negotiated blanket purchase agreements or multiple-award contracts can reduce the front-end labor requirement and streamline the buying process. In fiscal year (FY) 2012, the DoD conducted 14,263,469 transactions (accessed at usaspending.gov). Potential savings from process cost reduction by eliminating some of these transactions and transitioning from complex contract execution to ordering off strategic vehicles where possible can yield millions of dollars in process cost savings.

Demand

A third type of potential savings is demand savings. Demand savings focuses on reducing the total number of units purchased. Switching from incandescent light bulbs to LED bulbs is an example of reducing demand cost. By seeking out solutions that reduce the total number of products or services required in order to meet the mission, the DoD can reduce demand cost. Demand cost reduction can occur in multiple cost pools depending on the item. In addition to the item procured, it could also include maintenance time, inventory support, and other logistics cost that may be reduced (Reed et al., 2005).

Examples of Cost Savings in Air Force Strategic Sourcing

We now turn to an example of an Air Force (AF) sourcing strategy to illustrate the placement of cost causes into the three recommended categories. The AF Civil Engineering Support Agency (AFSECA) identified the conversion of taxiway lights to LED as a strategic sourcing opportunity in 2010. The AF had over 30,000 taxiway lights, which illuminate the edges of runways and taxiways at AF bases. One third of AF taxiway lights had already

been converted to LED by independent bases. However, there was no enterprise-wide approach to bulb conversion. As a result, the AF was not leveraging its purchasing power (rate-related cost). It was not incurring standardized inspection, electricity, and maintenance costs (demand-related causes of cost). Finally, it was inefficiently conducting procurement transactions (process-related causes of cost).

In early 2010, the newly formed Civil Engineering Commodity Council (CECC) took on the challenge to strategically source LED taxiway lighting with an enterprise-wide strategic approach. A cross-functional team of acquisition and operational professionals was formed. Base-level civil engineers, airfield managers, and flight operations were identified as the affected requirement owner's subject-matter experts. Program managers, data analysts, and contract specialists from the AF Enterprise Sourcing Group led the multi-functional team. The AF completed the sourcing strategy in October 2010 (Quinter, 2012). We examine the forecast reductions in causes of cost in the next section.

Rate Cost Efficiencies

The rate cost efficiency is based on the reduction in the price per unit paid for each LED type light. With more than 10,000 lights being replaced over the last year, energy savings are being realized. From a cost savings perspective, since being awarded, the contracts have been utilized to provide replacement lights at 18 AF installations in 10 states. Cost savings of 50–60% were anticipated, based on past spend for incandescent lamps. Although actual cost savings are still being calculated for the last quarter, $300,000 in cost savings has been confirmed (Quinter, Wilkins, Bell, Bowling, & Tungate, 2012). As we have discussed, leveraging buying power to reduce the price paid per unit is most often the initial focus for sourcing strategy teams. Although these savings can be significant at the outset, the source of enduring savings is in understanding and affecting the causes of cost in the process and demand categories.

Process Cost Efficiencies

By having a centralized contract vehicle, AF buying offices can now place orders off existing contract vehicles rather than creating new contracts or orders for each purchase. This reduces the amount of effort required to acquire taxiway lighting. The AF utilizes a process cost model to calculate process cost savings based on the number and type of transactions avoided as a result of new strategies.

Demand Cost Efficiencies

Demand cost efficiency in this example can also be seen as anything that occurs as a result of the strategy that reduces or changes consumption related to the item. In this case, two primary benefits were realized by the AF from moving to LED lighting. The first cause of cost that is affected by the strategy is energy consumption: The LED fixtures are designed to use 60% less energy than conventional lighting (Quinter et al., 2012). The AF validated energy savings by separately metering airfield lighting installed at one AF base and using the achieved reduction calculation as the per-unit energy savings factor. Total savings are calculated using an aggregation of expected energy savings multiplied by the number of units installed.

The second, cause of cost affected by the strategy is maintenance labor cost. The LED lights have an average life expectancy of more than 100,000 hours, compared to the 1,000 hours provided by the previous incandescent fixtures (Quinter et al., 2012). Due to the longer life of the LED fixtures, the airfield maintenance (inspecting and replacing burned out bulbs) is dramatically less. Because the incandescent bulbs burn out and need to be replaced much more frequently than the LED fixtures, which are virtually maintenance free,

the task of maintaining the fixtures is all but eliminated (except due to damage). Calculations utilizing average labor rates and observed labor touch times were used.

Recommendations

The adoption of strategic sourcing by government has been slowed by many factors. A significant barrier is that procurement organizations continue to be staffed primarily with single function workers with no experience in strategic procurement principles or techniques. The government is further limited by a focus on tactical execution of one requirement at a time rather, than an enterprise-wide, strategic perspective.

We acknowledge that organizational inertia in government is too powerful a force to overcome in the pursuit of changing the way these buying organizations behave. Rather, we suggest the establishment of new, multi-functional, multi-skilled organizations to create and execute sourcing strategies for the enterprise. Establishing these organizations requires a compelling business case based on the standardized identification of potential savings that are possible through strategic sourcing. Such a business case will likely demonstrate a significant ROI relative to the cost required to establish the organization.

We recommend developing a standardized methodology to identify, capture, and communicate cost causes, and subsequent savings is essential to securing the resources needed to implement successful sourcing strategies. As illustrated by the AF taxiway lighting example in this paper, using rate, process, and demand categories allows for a straightforward yet comprehensive collection of savings that result from the implementation of strategic sourcing.

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Software Acquisition

Managing Risk in Mobile Applications With Formal Security Policies

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Streamlining the Process of Acquiring Secure Open Architecture Software Systems

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Managing Risk in Mobile Applications With Formal Security Policies

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Abstract

Department of Defense (DoD) acquisition requires information technology (IT) to undergo the DoD information assurance certification and accreditation process (DIACAP), which makes strong architecture-dependent assumptions. Emerging IT architectures, such as mobile computing platforms, invalidate these assumptions and prevent the DoD from acquiring commercial technologies that are readily available to adversaries. To address this problem, we introduce a preliminary framework in which an application profile is expressed in a formal language and scaled with evolving architectural assumptions. This profile aims to incorporate information assurance (IA) requirements that are commensurate with risk and scalable based on an application's changing external dependencies. Information assurance risk levels that account for changing user identities and IA parameters (confidentiality, integrity, and availability) will result from dynamic recombination of mobile applications during runtime. The language is expressed in first-order logic and includes an evolvable lexicon to describe changing system configurations. We envision that software developers and certification authorities can use these formal profiles with an inference engine to complete the DIACAP and maintain compliance as IT systems evolve over time. The framework has been evaluated using existing DoD acquisition and DIACAP policy and a case study in a popular mobile application ecosystem.

Introduction

Network-centric (net-centric) warfare (NCW) is the "generation of increased combat power by networking sensors, decision makers and shooters" (Alberts, Garstka, & Stein, 1999). The Department of Defense (DoD) adopted NCW as a principle concept of operations as early as the late 1990s. This adoption includes increased efforts to move information from garrisoned to command posted and out to "the edge," or front-line combatants, to reduce the time from decision to action and create a more mobile, agile, and reactive force. During this transition, General Cartwright noted that NCW must decouple the chain-of-information from the chain-of-command (Onley, 2006; Carter, 2010) to enable the right people to gain access to the right information at the right time. Unlike enterprise information systems in garrisons and command posts, computing at the edge must be highly dynamic and responsive to fast-changing situations. This fast-paced environment yields rapidly changing software requirements, evolvable software architectures, and utility computing, which stress the current DoD acquisition system. The DoD acquisition challenge is that edge computing requires mobile applications, which are increasingly software-intensive, developed on shorter timelines, and subject to different cyber security risks (Defense Science Board, 2009).

The short IT development timelines have led commercially available IT to outpace the DoD's ability to rapidly acquire IT solutions. This is concerning when adversaries can acquire and deploy this technology worldwide and with few restrictions. Mobile computing platforms, such as Apple iOS and Google Android, offer a stark contrast to traditional computing paradigms because they enable the rapid development and deployment of commercial software to handheld devices, including tablets and smartphones. This software integrates data from multiple sources and significantly reduces the time from decision to action: New "apps" include software to complete banking transactions by digitally photographing bank checks, to purchasing music based on audio fingerprinting, to integrating mapping, routing, and directory services to locate nearby retailers, all within seconds. In these examples, apps leverage built-in devices, such as cameras, microphones, or geo-location technologies, to create narrowly integrated solutions. However, recent efforts to enable rapid DoD acquisition has focused on non-software-intensive systems (Carter, 2010; Wyatt, 2010).

Mobile computing introduces new IT security risks within a single IT system and collectively across multiple, networked systems. Unlike traditional non–software-intensive systems, IT security vulnerabilities can compromise other systems on a shared network. To reduce cyber security risk, the DoD Chief Information Office (CIO) maintains DoD Directive (DoDD) 8500.1 "Information Assurance" and DoD Instruction 8500.2 "Information Assurance Implementation," which outline policy, responsibilities, and procedures to integrate IT security protections into DoD information systems. Most DoD weapon systems subject to DoDD 5000.1 in the DoD Acquisition System must comply with these CIO policies. These policies are primarily written for enterprise systems, which excludes mobile computing as envisioned at the edge in NCW. The challenges of modernizing the IT acquisition policy have been attributed to a culture of buying large weapon systems, such as aircraft carriers, as opposed to incremental purchases of components that integrate into pervasive, complex systems (Boessenkool, 2009). Moreover, recent calls for modernizing acquisition have called for 80% solutions, which is a departure from complete, service-centric solutions that become outdated before they're completed (Gates, 2009). Mobile applications are exemplars of these modern acquisition challenges.

The U.S. Army has been a leader in the adoption of mobile applications in the DoD. In March 2010, the U.S. Army began the "Apps for the Army" challenge, which sought to test a rapid acquisition process for software applications on mobile devices. The challenge received 53 mobile applications, of which the Army successfully fielded 25 applications through the certification process (Lopez, 2010). In addition, the Army is actively engaged in training mobile application developers in its Mobile Applications Branch at Fort Gordon (Walker, 2011). Finally, the Army is taking steps to increase its mobile device infrastructure: After testing 20–30 smartphones in theater, the Army is now seeking to field 3,500 smartphones for a single brigade (Brewin, 2011). The Relevant ISR to the Edge (RITE) program recently completed testing and seeks to develop technologies to link critical data to soldiers in the field using smartphones, thus further pushing this paradigm forward (Montalbano, 2011). These steps further illustrate the need for adequate solutions to certify mobile applications.

In this paper, we propose a preliminary framework to model app IT-dependencies with the following long-term aims: (1) to reduce IA certification and accreditation time by semi-automatically matching IA assumptions to application profiles; and (2) to extend existing IA policy assumptions to cover emerging mobile applications required in edge computing. This paper is organized as follows. We first review DoD IT acquisition and IA policy environment and present policy gaps that inhibit acquisition of mobile applications;

next, we briefly present our framework, application profile, and language to address this problem; finally, we discuss our evaluation and plans for future work before concluding with related work and our discussion.

DoD Information Technology Policy

The DoD information technology (IT) policy environment is complex and distributed across multiple documents. The leading Department of Defense (DoD) policies for IT acquisition and information assurance (IA) are summarized in Figure 1. The general DoD acquisition policy and responsibilities are detailed in DoD Directive (DoDD) 5000.1, and the DoD-wide IA policy begins in DoDD 8500.1, which is refined by IA controls contained in DoD Instruction 8500.2 and by the process for performing IA certification and accreditation, described in DoDD 8510.1.

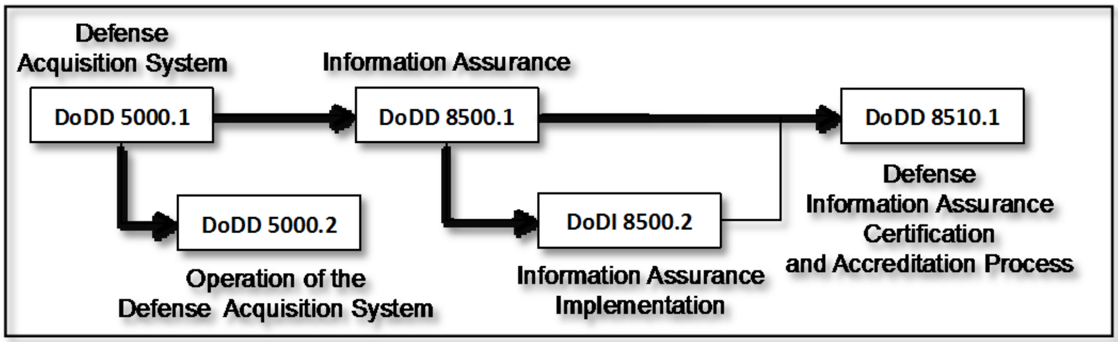

Figure 1. General Overview of the DoD IT Acquisition Environment for Information Assurance

DoDD 8500.1 governs information systems that include mobile computing devices, such as laptops, handhelds, and personal digital assistants (see DoDD 8500.1, § 2.1.2.7) and, in particular, those devices that contain wired or wireless network access to other computing resources. This instruction covers four classes of information system, as follows:

- *Automated Information System (AIS) Applications*, which are products of an acquisition program, such as software applications, or a combination of software and hardware, such as workstations, servers, and mobile computers;
- *Enclaves*, which are a collection of computing environments connected by internal networks, under the control of a single authority and security policy;
- *Outsourced IT-based Processes*, which are business processes supported by private sector information systems; and
- *Platform IT Interconnections*, which are network access points to computer resources that are essential to the mission in real-time.

Figure 2 illustrates an example IS environment, consisting of two enclaves, “A” and “B,” which correspond to a garrison and command post, respectively. These environments contain AIS applications (square boxes) and outsourced IT-based processes (circles), some of which are DoD controlled and appear within the enclave, and others that have shared control and appear outside the enclave. Platform IT Interconnections appear as solid black arrows: When these connections exit an enclave, a demilitarized zone (DMZ) is assumed to exist between the outgoing and incoming network traffic. Mobile computers, such as laptops and handhelds, are a class of AIS application that are capable of moving across enclave

boundaries; in Figure 2, the dotted-line arrows indicate movement of a handheld computer from the battlefield, into a command post, and later into a garrison. To enable this movement, IA controls must be in place to avoid contaminating these DoD controlled environments. For example, DoD 8500.1 defines the Mission Assurance Category (MAC) as the level of integrity and availability required by an information system. Enclaves always assume the highest MAC of their computer resources (AIS applications, outsourced IT-based processes, and platform IT interconnections). When an enclave connects to another enclave that has a lower MAC level, the enclave with the higher MAC level must ensure that this connection does not degrade the integrity and availability of its computer resources. This presents a particular challenge for mobile devices because they could move across enclaves.

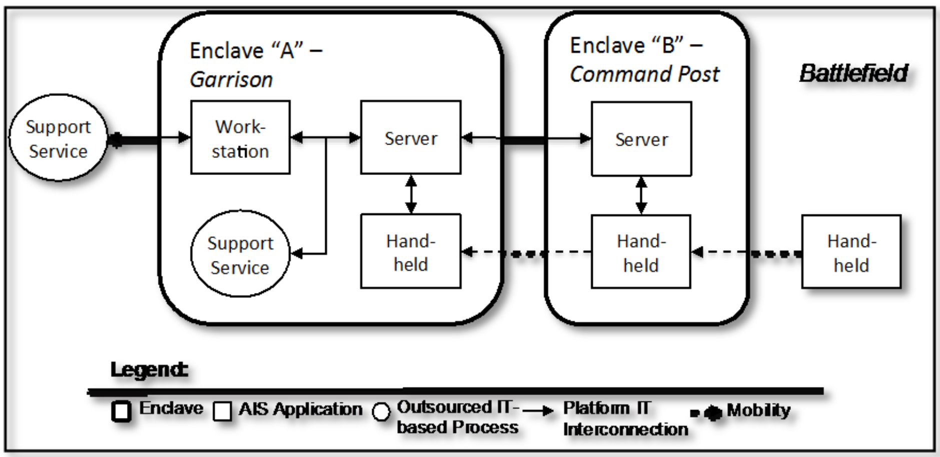

Figure 2. Example Information System Environment to Illustrate System Interactions

Applications for mobile computers, specifically handheld computers, have an operational profile that is situated among several policy gaps in existing IA policy. Under DoDD 8500.1, Designated Approving Authorities (DAAs) are responsible for certifying and accrediting these devices. Policy gaps create challenging certification environments in which the DAA must assume insurmountable risk for an unprecedented DoD information system. The combination of changing users, changing applications, and changing locations is characteristic of these devices. Consequently, a solution is needed whereby configurations can be reviewed dynamically in the field based on explicit IA assumptions that are individually bound to the mobile device hardware and collections of installed mobile applications. Figure 3 illustrates a subset of this complex policy environment: Boxes represent existing DoD IA-related policy; ovals represent IA controls from DoDI 8500.2; and arrows trace policy guidance from DoD8500.2 to IA controls and on to other applicable DoD policies. Using our requirements specification language (Breaux & Gordon, 2013), we extracted a core set of 95 requirements governing DoD IA responsibilities. We now discuss how these policies and IA controls apply to mobile applications, noting relevant shortfalls due to unique characteristics of this technology.

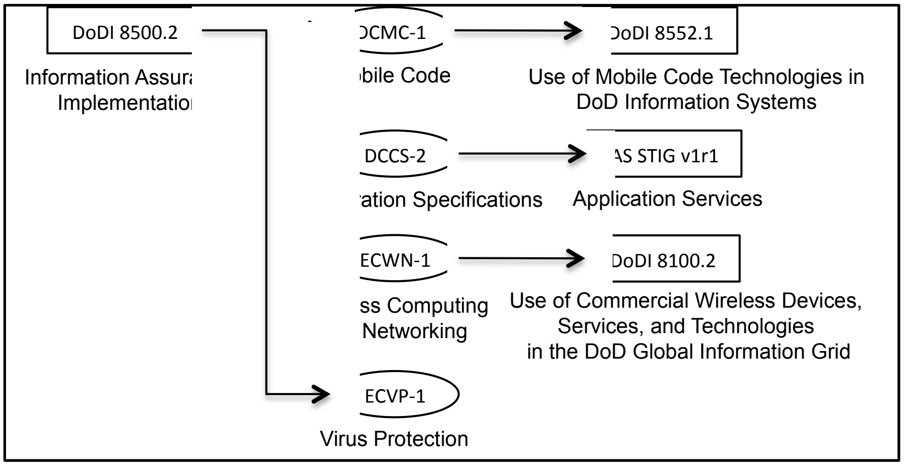

Figure 3. Example DoD Information Assurance Policy Gaps Affecting Mobile Applications

Mobile Code

Mobile code is defined by DoDD 8500.1 to be "software modules obtained from remote systems, transferred across a network, and then downloaded and executed on local systems *without explicit installation or execution by the recipient*." DoDI 8500.2 requires IA control DCMC-1, which requires implementing mobile code policy in DoDI 8552.1. This mobile code policy consists of approval decisions pursuant to one of three mobile code categories, which are differentiated by (a) whether the mobile code is digitally signed by a trusted certificate; and (b) the level of access to operating system resources and networks that is granted to the mobile code. Mobile computing is enriched by mobile applications (code) that can be downloaded and installed remotely to address emerging issues. However, the italicized phrase above in the mobile code definition excludes this policy from covering mobile applications, despite that many of the technical considerations (e.g., the mobile code category differentiators (a) and (b)) are relevant to mobile applications.

Mobility

DoDD 8500.1 defines mobile computing devices to include laptops, handhelds, and personal digital assistants operating in either wired or wireless mode. DoDI 8500.2 states that authorized users may "not relocate or change DoD information system equipment or the network connectivity of equipment without proper IA authorization" (§ 5.12.12), requiring advance IA authorization to move mobile computing devices. To employ compliant mobile computing devices, there is a need to rapidly reauthorize these devices as they move within and across enclaves, recognizing that these devices also contain mobile applications, which may change over time and thus change the device's risk profile.

Application Servers

The Defense Information System Agency (DISA; 2006) defines *application server* as a single computer that, in conjunction with other servers on a network, provides an application service to a user through a web browser. Application servers, such as Apache Tomcat and BEA Weblogic Server, are "containers" that provide application infrastructure while server administrators can remotely deploy applications that are pre-packaged as web application archives (WARs). DoDI 8500.2 contains IA control DCCS-2, which requires compliance with available security technical implementation guides, or STIGs. Only recently were new STIGs developed to cover mobile device operating systems (iOS, Android, or Blackberry OS). Previously, the DISA's STIG governing application servers, which requires responsibility for application server content to be assumed by the sponsoring organization or

activity (DISA, 2006), were the closest approximation of how mobile apps are installed on mobile devices, the main difference being that the STIG assumes that application servers are fixed in an enterprise information system.

Wireless Networking

Wireless computing and networking capability is not required, but it significantly amplifies mobile computing capabilities. DoDI 8500.2 contains IA control ECWN-1, which requires that workstations, mobile computing devices, and other portable electronic devices comply with DoD wireless policy. This policy includes DoDI 8100.2, § 4.3, that states that wireless devices may not be operated in classified environments without approval by the DAA in consultation with CSA CTTA; and § 4.10, which requires a knowledge management process to determine acceptable uses of wireless devices and appropriate mitigation strategies.

Virus Protection

DoDI 8500.2 contains IA controls ECVP-1, which require virus protection for servers, workstations, and mobile computing devices, such as laptops. For general-purpose computers, virus protection includes anti-virus software that recognizes file signatures that correspond to malicious code; this code is downloaded from a remote computer. Mobile devices running restricted operating systems, such as Apple's iOS or Google's Android, however, constrain the environment in which remote code can be executed. In these devices, mobile application infrastructure, including pre-approved applications in a trusted app store, can reduce or eliminate exposure to malicious code for some mobile applications.

Our analysis of the Android 2.2 STIG, Version 1, Release 1, yielded 59 requirements that affect mobile Android devices. Among these, 40 requirements target the operating system, 16 requirements target apps, and three requirements target external actions, such as ensuring that mobile users respect the physical security policy when using the smartphone camera. Requirements WIR-MOS-AND-006-01 and WIR-MOS-AND-006-3 require approval from the DAA or application control board for all non-core apps. This includes an inspection of the app and risk analysis. Although some tools exist to conduct static analysis on source code to identify common vulnerabilities (e.g., buffer overflows), to our knowledge no tools exist to analyze mobile app requirements for the purpose of identifying security risks. As a result, the current guidance is inadequate to support the DAA in evaluating non-core apps. Therefore, we now discuss our framework that aims to begin to address this problem.

Mobile Application Framework

Mobile devices that run pre-approved mobile applications can be viewed as miniature enclaves, in which the user has the authority to reconfigure and recompose new functions from multiple AIS applications (mobile apps) and initiate connections to pre-approved outsourced IT processes using platform IT interconnections. Unlike general-purpose computing enclaves, these applications, processes, and interconnections operate on pre-defined data types in a restricted computing environment. Some mobile applications leverage general-purpose data types, such as e-mail clients or web browsers, but most use restricted data types, such as dates, locations, images, audio, and so forth. Advances in miniaturization may lead to mobile devices that run multiple computing environments in parallel, in which each environment processes different information classes with approved guards for moving unclassified data into classified environments within the same mobile device. For example, recent work has demonstrated the ability to run multiple mobile OSes on the same device using virtualization (Suh et al., 2008). Finally, we envision that mobile devices can be moved between enclaves, which changes the runtime assumptions under

which mobile applications are permitted to operate. Mobile applications approved to handle unclassified data cannot operate in classified physical and cyber environments without approved guards to prevent the unauthorized release of classified data. Similarly, classified applications cannot operate in unclassified environments.

Figure 4 illustrates several challenges to accrediting mobile applications. In Step 1, Figure 4, application (app) developers create an application profile in the EADL for their app based on the mobile application system architecture. In the future, this profile may be generated using code-level analysis to assist in certification (e.g., do network connections use OS SSL libraries, or does file I/O encrypt data in storage?). In Step 2, the DAA certifies the app using the application profile and may accredit the app for deployment to the mobile device under this profile. The certification and accreditation includes a digital signature of the application profile, which the mobile device will use to execute the application only in enclaves that conform to this profile. In Step 3, the signed app is loaded into a DoD app store, authorized users can download the app to their mobile device.

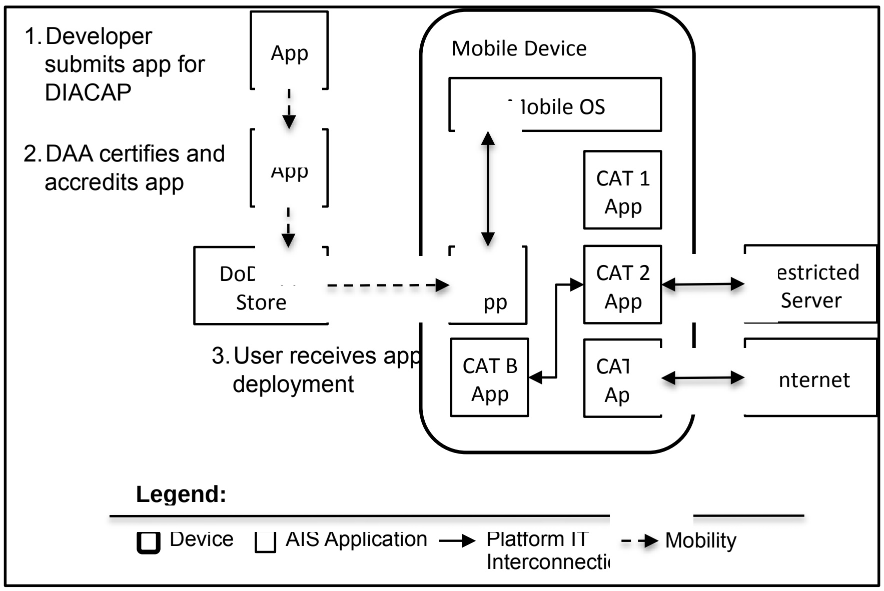

Figure 4. Example Life Cycle for a Mobile Application in a Handheld Device

In our framework, mobile applications are assigned to different categories based on their resource utilization profile. We envision the following categories: CAT 1, 2 or 3, which describe the level of remote connectivity, may be combined with CAT A and B, which describe the type of local interactivity. These categories were validated based on our analysis of DoD IA policy.

- **CAT 1:** *Stand-alone apps* are installed with their complete data set, such as training manuals, calculators, or dictionaries. These apps do not make connections to remote servers or the Internet.
- **CAT 2:** *Restricted apps* periodically make connections to pre-approved servers only. These apps include weather services and route-finding applications that receive updated maps from pre-approved sources.
- **CAT 3:** *Unrestricted apps* may make connections to remote servers that are unsecured or not on a pre-approved list. This includes web browsers.

- **CAT A:** Apps may use specialized operating system resources, such as cameras, microphones, speakers, GPS coordinates, and so forth.
- **CAT B:** Apps may exchange pre-defined data types with other apps.

We examined descriptions of mobile applications in the context of current initiatives in the United States Army. Among the five winners of the Apps for Army Challenge, three Apps could be developed as CAT 1 apps (New Recruit, Physical Readiness Trainer, and Telehealth Mood Tracker): The first two apps provide access to stable knowledge bases that can be updated periodically in new, self-contained versions of the application; these may include hard-coded web pages, training videos, and so forth that reside locally on the mobile device. The remaining two winners, Movement Projection and Disaster Relief Operations, appear to be CAT 2A apps: They rely on map-routing data that can be acquired from an approved source, such as Google Earth and Google Maps. If these connections are not secured, they could leak information to intermediaries who route the data to the map server, which is a CAT 3A app. We envision that these categories can be further subdivided; for example, CAT A can be subdivided to distinguish the use of a mobile camera, versus the use of location-based services and accelerometers. We further envision static analysis tools that can be developed to analyze the source code of these apps to automatically determine which category the app falls within.

Mobile Application Profile and Language Overview

The mobile application profile is described by a set of requirements to express data flows for a single mobile application. These requirements are formalized in the description logic (DL) using the semantic parameterization method (Breaux, Antón, & Doyle, 2008). Based on our mobile application framework, an certification authority may want to prove that, for a given configuration (collection of mobile applications), no CAT 3A apps are operating during field operations that could disclose a soldier's location to an untrusted, third-party server, or that no communications exist between CAT 2B and CAT3B apps that may disclose sensitive data to third parties.

To achieve this aim, we begin by formalizing a subset of data requirements using three Deontic modalities: *Obligations* describe what the app is required to do; *prohibitions* describe what the app is prohibited from doing; and *permissions* describe what the app is permitted to do. Formal requirements analysis is used to identify conflicts between what is permitted and what is prohibited, noting that obligations imply permissions in Deontic Logic (Horty, 1993). In addition, we define a series of roles based on Fillmore's (1968) case frames and Gruber's (1976) thematic roles to encode the actors engaged with the data, the type of data, and the purpose for which the data is used. At present, the restricted set of requirements covers only three specific actions: *Collection*, which is any act to access, assign, collect, import, observe, or receive information from another party, sensor, or device; *transfer*, which is any act to disclose, provide, share, or transfer data to another party; and *use*, which is any action performed on the data by the app for a particular purpose, excluding collections and transfers. The set of data requirements expressed formally constitutes the data flow aspect of the mobile application profile. App developers can formalize these statements using their knowledge of the app's operations, or by using stated natural language requirements, scenarios, or privacy and security policies written specifically for the app. We now illustrate this formalization using an example natural language statement from a written policy.

Figure 5 portrays a statement that has been encoded using the formalism; a more complete description of the formalization and an empirical case study is described in Breaux and Rao's (2013) study. In Step 1, the analyst identifies important keywords that indicate the

action (e.g., import, enter), the modality, and the role fillers: the *object* (e.g., address book contacts) is the data type, and the *purpose* (e.g., locating contacts) for which the data will be used. Because the verbs *import* and *enter* denote the movement of data from the user to the app, these verbs indicate a collection. In Step 2, the keywords are written into a simple SQL-like syntax that encodes a permission, indicated by the language operator P, followed by the action name and the role fillers. The first role filler is the object, followed by the language keyword FOR that precedes the purpose for which the action COLLECT is performed. Using DL, we can express complex hierarchies of data types, actor roles, and purposes. These hierarchies allow us to check whether permissions that broadly allow information sharing of coarsely described information types conflict with prohibitions restricting the sharing of specific types. Conflicts of this type frequently arise due to exceptions in security policies.

Finally, in Step 3, an automated tool parses the language syntax and compiles a DL expression in the Web Ontology Language (OWL). The compiled expression is denoted in Figure 5 by the two axioms for concept p_8: The first axiom defines the concept p_8 as a collection action with the appropriate role fillers; the second axiom defines the concept p_8 to be a subclass of what is permitted. Using a theorem prover, we can check these profiles for internal consistency (i.e., are there any conflicts among the encoded data requirements?). We can also check these mobile application profiles for consistency with external properties by expressing these properties in the formal language, such as prohibiting transfers to third parties of certain data types (e.g., e-mail addresses). Using DL, we reduced data requirements conflict detection to DL satisfiability, which is known to be PSPACE-complete for this family of DL.

Step 1: Annotate policy text

Modal phrase "may" indicates an assumed permission

Collect keyword

Datum

We may also offer you the ability to import your address book contacts or manually enter e-mail addresses so that you can (i) locate your contacts on Zynga; and (ii) invite those contacts to join you in our games.

Purposes

Step 2: Write expression in specification language (P = Permission)

P COLLECT addess-book-contacts FOR locating-contacts,inviting-contacts

Step 3: Compile language into Description Logic (OWL)

$$p_8 \equiv \text{COLLECT} \sqcap \exists \text{hasObject.address-book-contacts} \sqcap \exists \text{hasPurpose.(locating-contacts} \sqcup \text{inviting-contacts)}$$

$$p_8 \sqsubseteq \text{Permission}$$

Figure 5. Example Encoding of Data Requirement Into Formal Language

Case Study and Simulation

At present, the language has been developed and validated using information privacy policies that describe privacy and security requirements, such as what information may be collected, used, and transferred, for what purposes, and by whom. These activities architecturally describe an app's data flows and, based on the providers and recipients of the data described in these policies, these activities frame the app in a larger information ecosystem that consists of the cellular network provider, the mobile phone and operating

system manufacturers and third-party service providers upon whom the app depends. Each of these ecosystem members maintain separate privacy policies that describe what is permitted and prohibited with respect to personal data. In addition, privacy has been viewed as a “subset of security” because these same information-sharing policies also affect confidentiality, integrity, and availability of the system: Companies often aim to increase information availability and integrity to improve their services, while users wish to increase confidentiality of personal information. Best security practices, such as complex passwords, data encrypted in storage and in transfer, and so on, have also been described in these policies. Finally, these policies are increasingly required by regulators and mobile app stores, such as Google Play and iTunes, which makes these policies a pervasive, publicly available, and rich source of security requirements upon which to develop a preliminary data-flow language for assessing our mobile security risk framework.

Our case study to evaluate the language’s formal semantics focused on the analysis of three policies that are linked in an integrated service scenario (Breaux & Rao, 2013). The scenario consists of the Facebook social networking platform, the Zynga game service, and AOL advertising network: Each of these parties has separate policies that govern the user’s interaction with Zynga online games, such as Farmville. Analyzing these three policies yielded 374 statements, of which 144 statements were data security requirements that were expressed in the formal language. Among these, the analysis produced two critical conflicts that we detected with our automated theorem prover: One conflict was between the Zynga policy and the Facebook policy because Zynga reserves the right to share information obtained from Facebook in violation of Facebook’s application developer’s policy.

Finally, we built tools to parse and reason about these policies. Our simulation studies, which are based on these tools, show that identifying conflicts can be performed within a reasonable amount of time (a few minutes) for profiles containing on the order of 100 rules. The simulation evaluated conflict detection using three different DL theorem provers: the Pellet OWL2 Reasoner v2.3.0 developed by Clark and Parsia, the HermIT Reasoner v1.3.4 developed by the Knowledge Representation and Reasoning Group at the University of Oxford, and the Fact++ Reasoner v1.5.2 developed by Dmitry Tsarkov and Ian Horrocks. Conflict detection for HermIT and FaCT++ was shown to be linear and constant, respectively, with respect to the number of rules. The Pellet reasoner was unable to scale beyond four rules in our simulation due to a design decision in this version of Pellet regarding how they handle a certain class of DL expressions. In future work, we aim to optimize conflict detection for larger policies, as needed.

Future Work

In future work, we plan to investigate three extensions to the mobile app framework and language. First, we aim to enhance our technical approach by developing framework extensions to link security specifications among multiple, separate apps. These extensions would allow an analyst to trace data flows across multiple apps and thus check whether security properties are held across these apps and their third-party services. We already have preliminary evidence to demonstrate this extension. Second, we aim to extend our framework to investigate how security policies change as mobile devices move across enclaves. This requires establishing and comparing physical security policies for physical locations with policies for apps that interact with those locations, either through user data entry, location-based services, cameras, or other means. As we discussed with Figure 2, we aim to support graceful degradation to limit the services that become disabled to only those that are not trusted in high security enclaves. Finally, we aim to extend our formal language with additional security properties to describe how data is properly stored, what attributes must be true during collections and transfers, and so forth.

In this paper, we described an overview of the approach and summarized our evaluation based on policy analysis and a runtime simulation. In the future, we seek to study the use of our framework in an experimental setting to answer questions, such as the following: How well can app developers write security specifications for their apps using our framework, and how well can certification authorities use these specifications to assure the app conforms to security best practices? We imagine that new interfaces to our formal methods would be needed and that static and dynamic analysis tools could help authorities verify that app runtimes conform to the stated app security profile.

Related Work

Related work includes enterprise architecture languages, which are used to express relationships between IT resources at a system-wide level, other work to analyze information assurance policy in privacy and security, and work to model information assurance properties in systems. Enterprise architecture (EA) is an informal concept consisting of four layers: business, information, applications, and technology. The layers provide notional constructs for capturing the range of personnel roles, responsibilities, assets, and functional system requirements. The Open Architecture Framework (TOGAF; The Open Group, 2009), Department of Defense Architecture Framework (DODAF; DoD CIO, 2010), and Zachman's Framework (Zachman, 2008) provide business analysts with guidelines and worksheets to capture architectural elements, but none of these frameworks use formal languages to enable model checking to find inconsistencies and conflicts within an architecture. Alternatively, Breaux and Powers (2009) found the Business Process Modeling Notation (BPMN), a declarative language for describing business processes, to be ineffective to express necessary temporal constraints in policy requirements. Ouyang, van der Aalst, Ter Hoftede, and Mendling (2009) asserted that the Business Process Execution Language (BPEL), preferred as the candidate formal semantics for BPMN, only works for limited classes of BPMN models (Ouyang et al., 2009).

Extensive work has been done to model information assurance policies. Breaux developed an early framework to extract privacy and security requirements from regulations (Breaux, Vail, & Antón, 2006), which was later validated in the context of healthcare (Breaux & Antón, 2008). This work led to the development of a requirements-specification language to further automate the encoding process (Breaux & Gordon, 2013). More recently, this work has been formalized using DL to model-check requirements (Breaux et al., 2008) and to trace requirements across mobile application policies (Breaux & Rao, 2013). Breaux has studied the gap between security policy and functional requirements and found a need to express both elements of physical and cyber security architecture in the same language to reason about modern vulnerabilities in distributed systems (Breaux & Baumer, 2011).

Discussion and Summary

In this paper, we presented a mobile application framework that can be used to map existing DoD IA policy onto emerging mobile devices. The aim of the framework is to identify opportunities for new methods and tools to decrease the time required to assure that mobile devices and their applications conform to IA policies. Our approach consists of a taxonomy for classifying mobile apps based on different security risks and an application profile and language for describing data flows within mobile apps that can be used to check for security conflicts. The profile describes what information is collected, used, and transferred, and for what purposes; and the language is used to express the profile formally and to identify conflicts within and between profiles using automated theorem proving. In future work, we plan to extend the framework with extensions to address potential policy conflicts across physical locations as mobile devices traverse different enclaves. In addition, we aim to

experimentally evaluate this approach with mobile app developers and certification authorities responsible for verifying that these apps conform to relevant policy.

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Streamlining the Process of Acquiring Secure Open Architecture Software Systems

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Abstract

We present results from our ongoing investigation of how best to acquire secure open architecture (OA) software systems. These systems incorporate software product line (SPL) practices that include closed source proprietary software and open source software (OSS) components, where such components and overall system configurations are subject to different security requirements. The combination of SPLs and OSS components within secure OA systems represents a significant opportunity for reducing the acquisition costs of software-intensive systems. We seek to make this a simpler, more transparent, and more tractable process. Such a process must be easy to reuse, adapt, and streamline for different system application domains in order to realize cost reductions and improve acquisition workforce capabilities. Further, such a process should be aligned with Better Buying Power initiatives addressing OA systems, improved competition, defense affordability, and acquisition workforce improvements. We identify different ways and means for how to streamline the acquisition process for secure OA software systems through a focus on doing more with limited resources. Along the way, we pay particular attention to revealing how software licensing practices can affect cost in ways that hamper or better the buying power of acquisition programs.

Introduction

Our focus in this effort is to identify ways and means for streamlining the acquisition process for secure open architecture (OA) systems. These OA systems often rely on the integration of components that are independently developed by different software producers and made available as either open source software (OSS) or proprietary closed source software executables. Program managers, acquisition officers, and contract managers will increasingly be called on to review and approve security measures employed during the design, implementation, and deployment of OA systems (Department of Defense [DoD] Open System Architecture [OSA], 2011). Our effort builds on both our prior acquisition research (e.g., Scacchi & Alspaugh, 2008, 2011, 2012a) and related acquisition research efforts at the Program Executive Office (PEO) Integrated Warfare Systems (IWS; Guertin & Clements, 2010; Guertin & Womble, 2012; Womble, Schmidt, Arendt, & Fain, 2011), the Department of the Navy (Mactal & Spruill, 2012), and the Software Engineering Institute (SEI) that address software product lines (SPLs; Bergey & Jones, 2010; Jones & Bergey, 2011; Northrop & Clements, 2007). It is also influenced by related research in the DoD community addressing OSS (Defense Information Systems Agency [DISA], 2012; Hissam,

Weinstock, & Bass, 2010; Kenyon, 2012; Martin & Lippold, 2011], component-based software ecosystems (Scacchi & Alspaugh, 2012b; Reed, Benito, Collens, & Stein, 2012), and Better Buying Power (BBP) initiatives (Defense Acquisition University [DAU], 2012).

OSS represents an integrated web of people, processes, and organizations, including project teams operating as virtual organizations (Scacchi, 2007, 2009, 2010). There is a basic need to understand how to identify an optimal mix of OSS within OA systems as products, production processes, practices, community activities, and multi-project (or multi-organization) software ecosystems. However, the relationship among OA, OSS, security requirements, and acquisition is poorly understood [cf. Scacchi, 2009, 2010; Scacchi & Alspaugh, 2011, 2012b; Naegle & Petross, 2007]. Subsequently, from 2007–2008, we began by examining how different OSS licenses can encumber software systems with OA, which therefore give rise to new requirements for how best to acquire software-intensive systems with OA and OSS elements (Scacchi & Alspaugh, 2008).

As a result of our recent acquisition research efforts, we have been able to demonstrate that it is both possible and feasible to develop OA systems that incorporate best-of-breed software components, whether proprietary or OSS, in ways that can reduce the initial and sustaining acquisition costs of such systems.

We believe that such results are applicable to both enterprise information systems, which are widespread throughout the DoD and the U.S. government, as well as command and control (C2; e.g., Reed et al., 2012; Scacchi, Brown, & Nies, 2012; Scacchi & Alspaugh, 2013b) and other defense systems. Doing so, however, requires new guidance, and ideally automated tools, for explicitly modeling and analyzing the architecture of an OA system during its development and evolution, along with modeling and annotating the architecture with software component license rights and obligations. Our results thus demonstrate a major technological advance in the acquisition and development of OA systems, as a breakthrough in simplifying software license analyses throughout the contracting activities. Creating similar advances for streamlining the acquisition process, while reducing the costs of secure OA systems, is the next breakthrough that is needed.

In this paper, we describe ways and means for how to articulate, tailor, and streamline the process for how to simply and transparently specify and assess OA system security when acquiring different kinds of OA systems, and to do so in ways that highlight opportunities for cost reduction through system security requirements specification and OA system acquisition process streamlining. We provide examples of complex software elements that are applicable to many kinds of software-intensive systems within the DoD as well as within other government agencies and industrial firms. But we start in the next section by reiterating BBP principles and initiatives that guide this research by focusing on how to promote competition in the acquisition and development of secure OA systems.

Open Architecture and Better Buying Power

BBP (see http://bbp.dau.mil/) is part of the DoD's mandate to do more without more by implementing best practices in acquisition. BBP identifies seven areas of focus that group a larger set of 36 initiatives that offer the potential to restore affordability in defense procurement and improve defense industry productivity. One of the seven areas focuses on promoting competition, and this area includes an initiative to "enforce open system architectures and effectively manage technical data rights" (DAU, 2012). Technical data rights pertain to two categories of intellectual property (IP): they refer to the government's rights to (a) technical data (TD; e.g., product design data, computer databases, computer software documentation) and (b) computer software (CS; e.g., source code, executable code, design details, processes, and related materials). These rights are realized through IP

licenses provided by system product or service providers (e.g., software producers) to the government customer, so long as the customer fulfills the obligations stipulated in the license agreement (e.g., to indicate how many software users are authorized to use the licensed product or service according to a fee paid). As already noted, our acquisition research has focused on issues addressing OA systems and IP licenses since 2008 (Scacchi & Alspaugh, 2008).

OA software systems offer the potential to improve acquisition by providing new ways and means to acquire, develop, deploy, and sustain software-intensive systems. These new ways and means in turn may transform how the DoD acquires complex systems by moving away from long-duration, proprietary (closed) system architecture, and the difficult-to-control cost of system development efforts, towards systems that may be more rapidly assembled/integrated in an OA manner with more transparent costs. Such a transformation may in turn reduce vendor lock-ins that oftentimes are associated with rising costs to sustained deployed systems that are inaccessible to competing vendors. So closed architecture legacy systems are often subject to IP licenses whose consequence is to reduce competition while increasing system sustainability costs. Our research on OA systems dating many years back (Scacchi & Alspaugh, 2008) has consistently been aligned with efforts for improving competition in software system development and evolution through an investigation of innovative ways and means to acquire/develop component-based OA software systems that are subject to diverse, heterogeneous IP licenses (Alspaugh, Scacchi, & Asuncion, 2010). But there is more to do to improve competition and defense affordability while effectively managing technical data rights when addressing the acquisition of secure OA systems. In particular, this includes understanding that the processes for acquiring such systems are facilitated or constrained in light of overall BBP guidance and best practices as well as how best to improve and streamline these processes. These topics are our focus in the remainder of this paper.

How Better Buying Power Impacts the Processes for Acquiring OA Systems

The move to OA systems represents a transition from the acquisition of monolithic systems to the acquisition of reusable system components that can be integrated to realize different configurations of a software product family for a specific application domain (Bergey & Jones, 2010; Guertin & Clements, 2010; Jones & Bergey, 2011; Reed et al., 2012; Scacchi & Alspaugh, 2012b; Northrop & Clements, 2007; Womble et al., 2011). These components are acquired within a software ecosystem that is evolving towards component provisioning within open repositories, where components from different producers are available for selection, evaluation, and system integration (Guertin & Womble, 2012; Martin & Lippold, 2011; Reed et al., 2012; Scacchi, 2007; Scacchi & Alspaugh, 2012a, 2013b). Figure 1 provides a graphic view of how such an ecosystem spans from a sample of software producers and components through system integrators to software consumers/users.

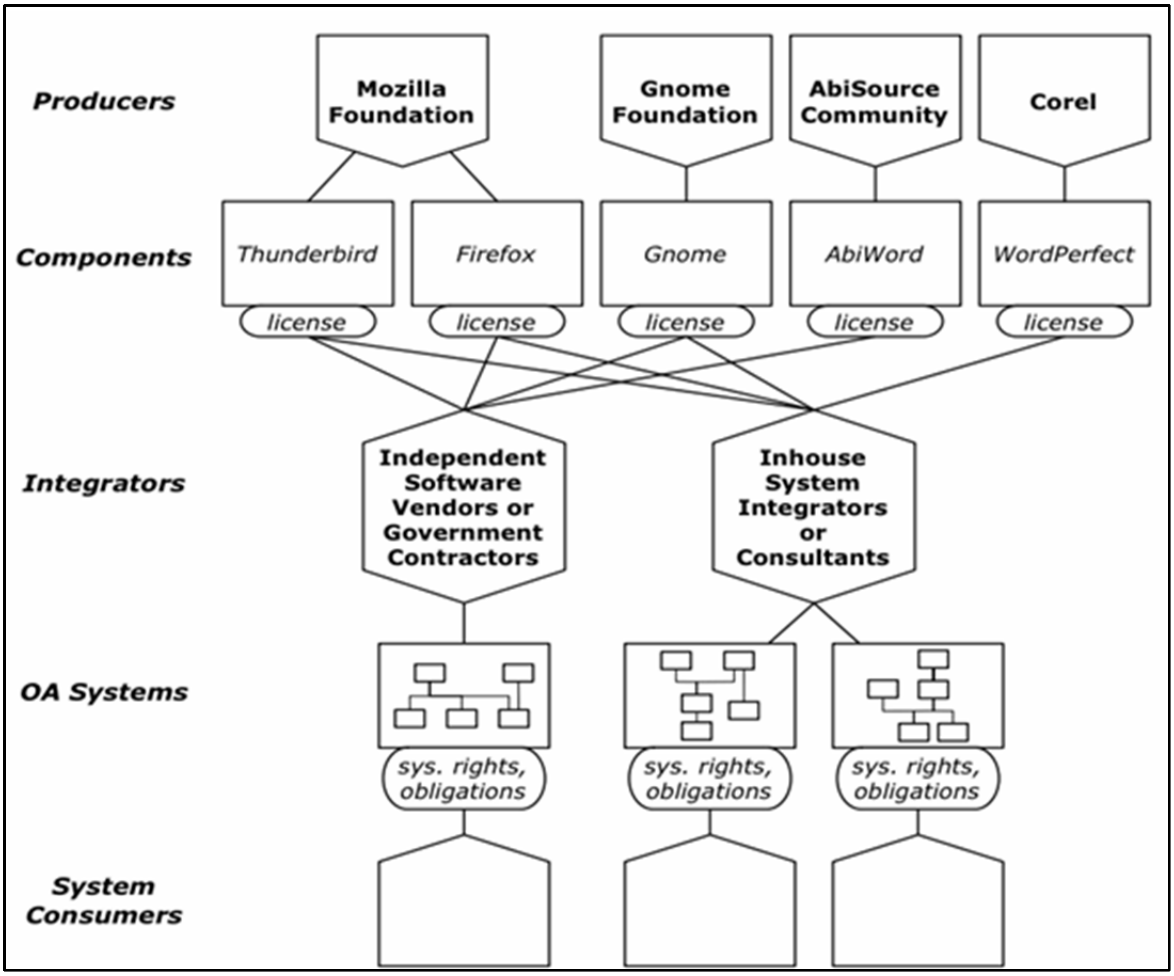

Figure 1. A Sample Software Ecosystem of Producers, Components, Integrators, Alternative OA Systems, and Consumers/Users
(Scacchi & Alspaugh, 2012b)

Figure 2 provides a view of a sample of lightweight software components ("widgets" targeted for software developers or integrators in this example) for download and installation within a Web browser. These widgets, made by different producers, are available for acquisition from Google's Chrome Web Store.

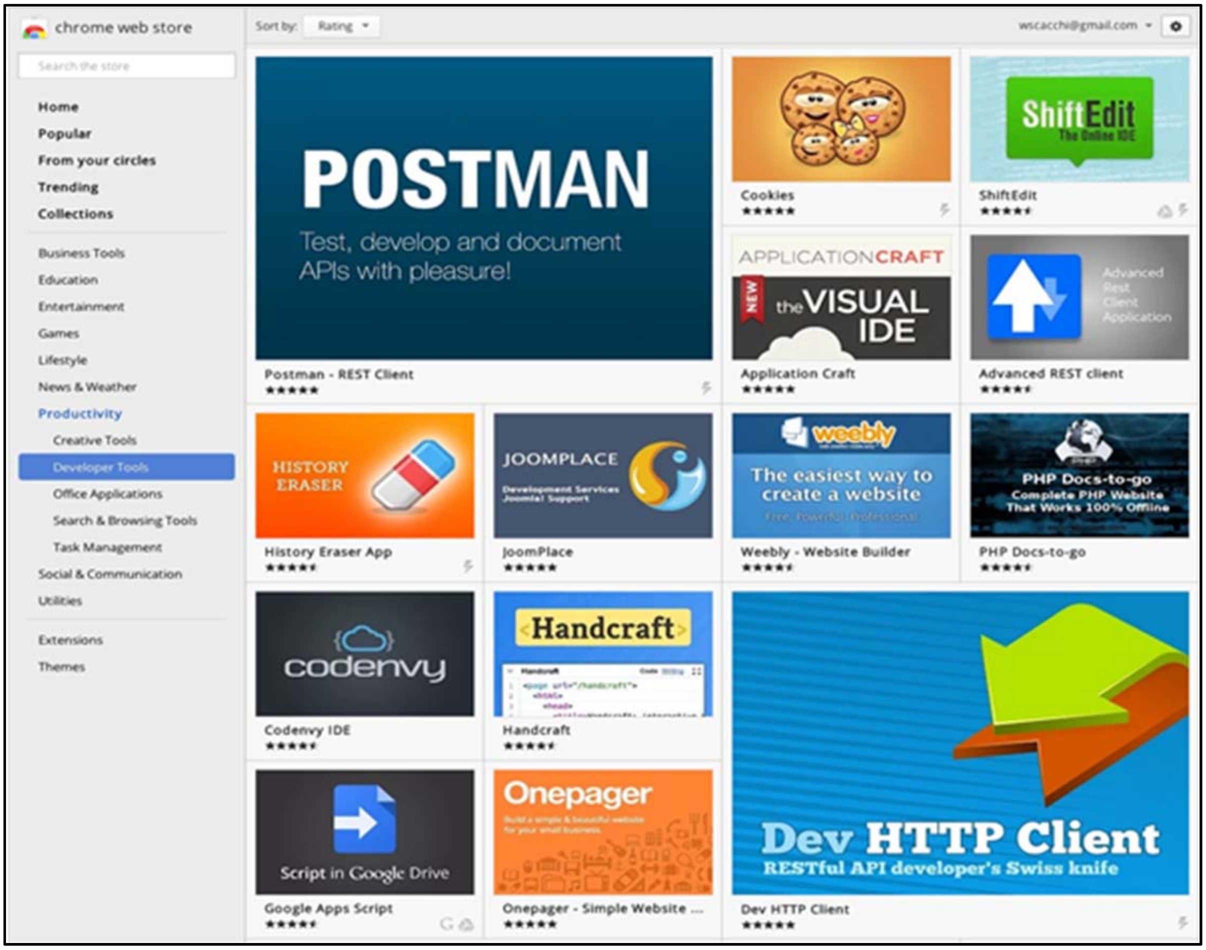

Figure 2. A Sample View of Lightweight Software Components ("Widgets") That Can Be Readily Acquired for Evaluation or Integration From Google's Chrome Web Store

Such an online store serves as a marketplace that provides access to ready-to-run, closed source software executables from within an online software repository that can be navigated using the menu on the left side, browsed by scrolling, or accessed by entry of a search term/phrase in the upper-left corner (see Figure 2).

Software components in an online marketplace like this are rated or recommended by other consumers, but the IP licenses for the TD and CS are hidden away with each component and may be challenging to locate prior to installation. Google Play for Android Apps and the Apple App Store also offer software (widget) components for their respective computing platforms (Android and iPhone smartphones, or Nexus and iPad mobile tablet computers).

Figure 3 provides a view of a different online repository that exclusively features OSS components found at SourceForge.net (similar to Forge.mil [DISA, 2012; Martin & Lippold, 2011]), where the IP licenses for each software component are prominently displayed when one selects to look more closely into the details and development status of a component of interest. In contrast to the Web-browser-specific software widgets available at the Chrome Web Store, the OSS components at SourceForge.net represent more substantial, production-oriented software tools or utilities that can operate as stand-alone application

programs. Forge.mil may be envisioned to provide support for accessing pre-tested and certified software components, whether lightweight widgets or more substantial application systems, in OSS code and ready-to-run executable forms with technical data rights designed for government purposes. Thus overall, what we see is that if we want to improve competition through the acquisition of component-based software systems, our choice of which online repository or marketplace to use leads to different kinds of software components with different IP license schemes.

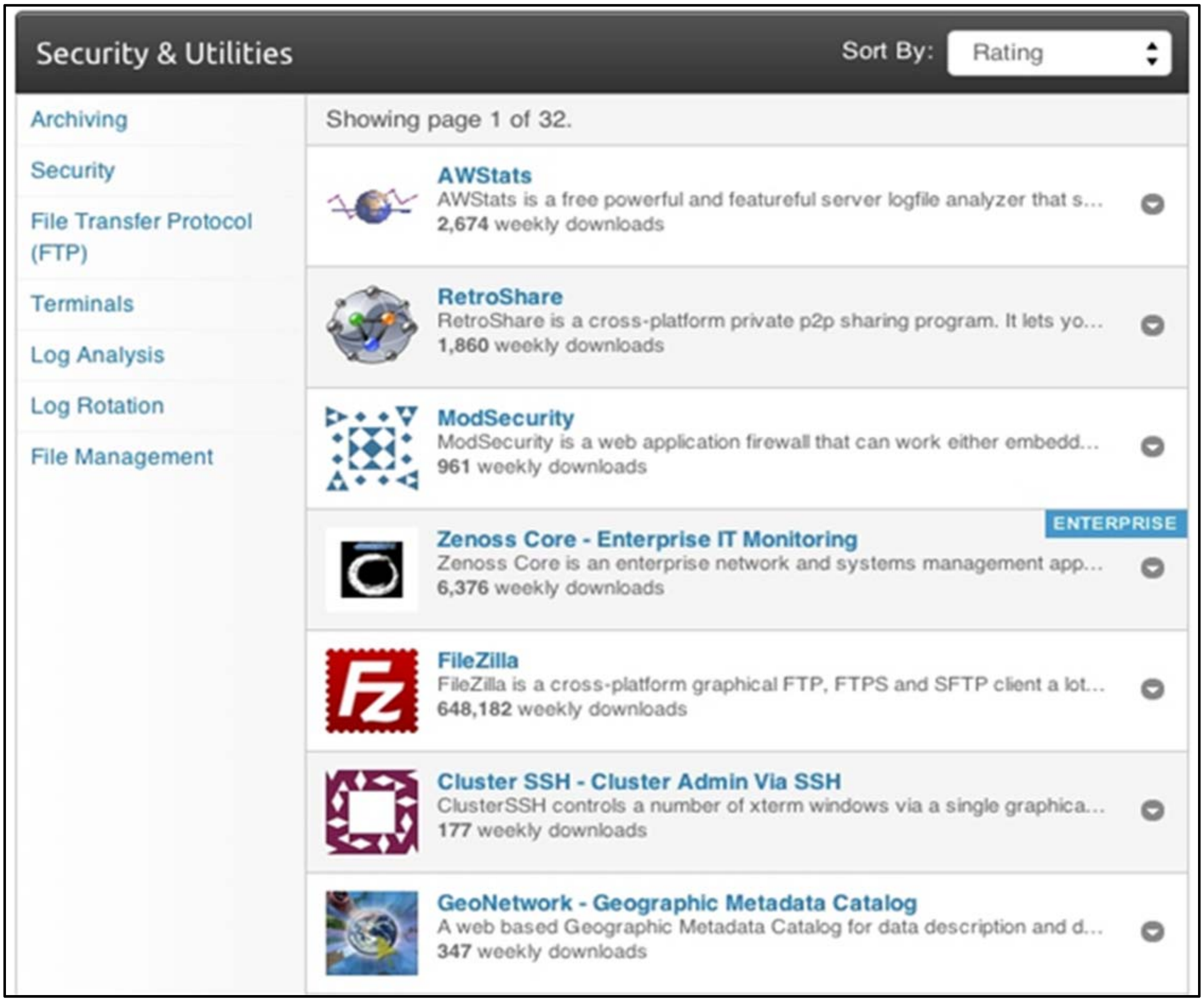

Figure 3. Sample of OSS Security/Utility Components Found at SourceForge.net

Next, we encounter challenges in the development of integrated OA systems that are configured from different software components. Figure 4 provides a visual representation showing that different software producers can develop different kinds of software components (small, medium, or large size/capability), which system integrators can select from in order to create an OA system product line of alternative component configurations.

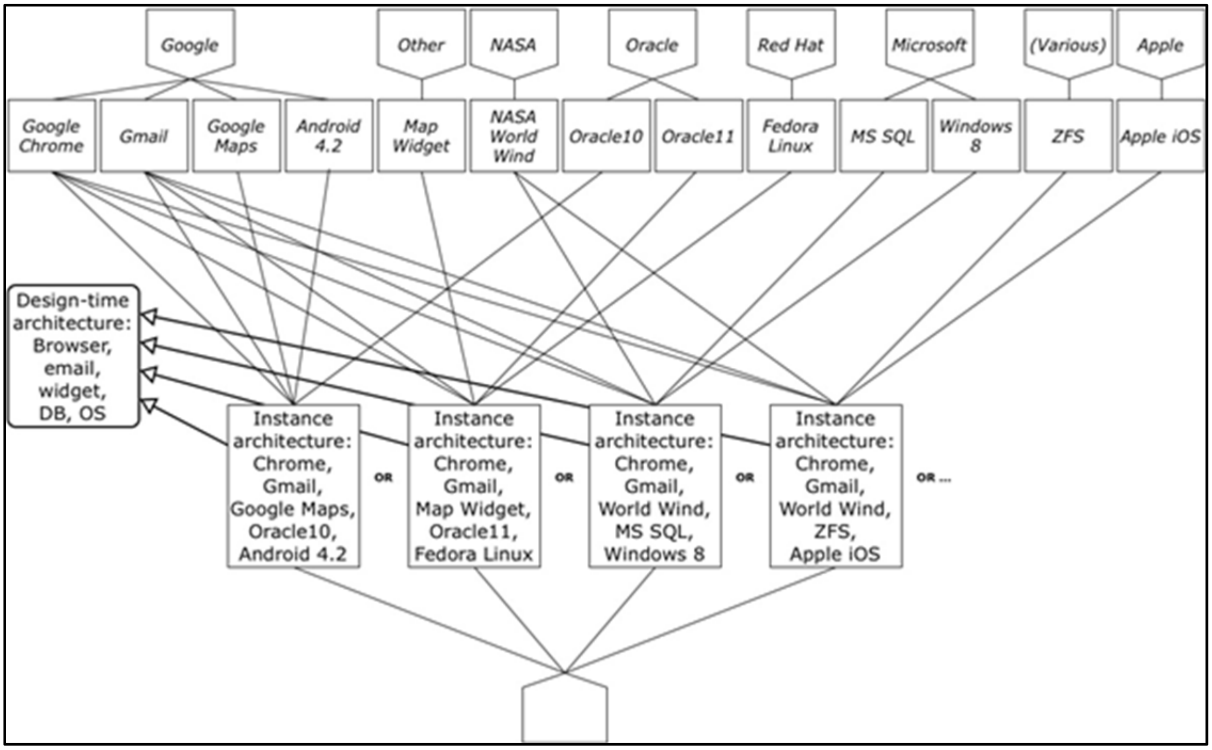

Figure 4. A Component-Based Software Ecosystem That Configures a Product Line of Four Alternative System Configurations, Conforming to an OA System Design in Figure 5

Figure 5 shows a simple OA system design that accommodates alternative software components as applications or infrastructure elements that may be subject to OSS or proprietary licenses. The applications (“apps”) may include small, proprietary, and lightweight browser widgets or large components like OSS-based Web browsers. The infrastructure software, which is assumed to serve as an independent foundation for application software, can include proprietary or OSS components like database management systems (or network file systems or other online repositories) and computer operating systems. Figure 6 displays the selection of one set of conforming software components selected from the software ecosystem in Figure 4 that also conforms to the OA system design in Figure 5.

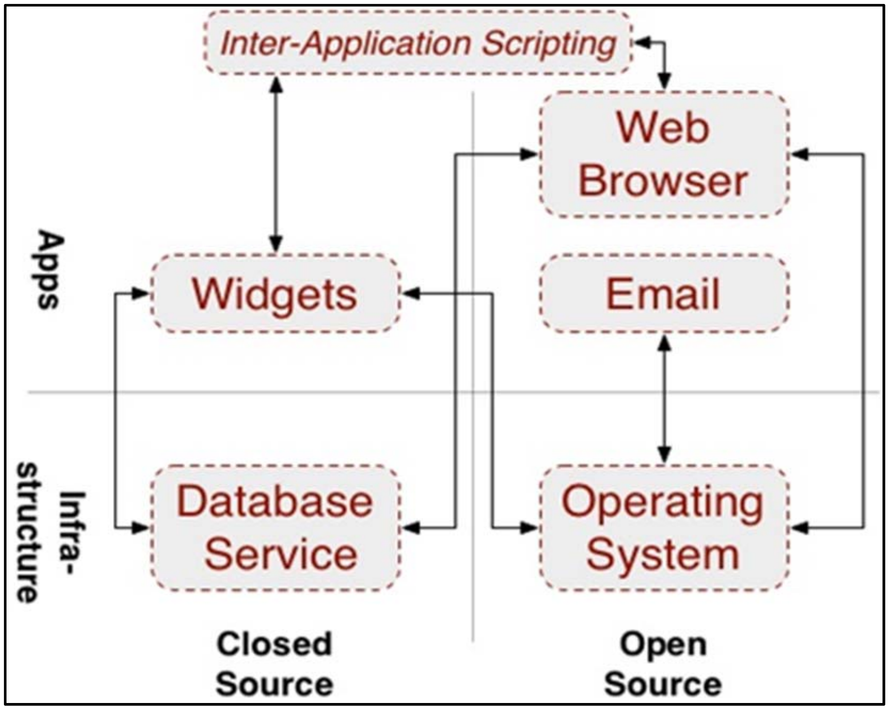

Figure 5. A Simple OA System Design That Accommodates Software Components as Applications or Infrastructure Elements, Shown in Figure 4

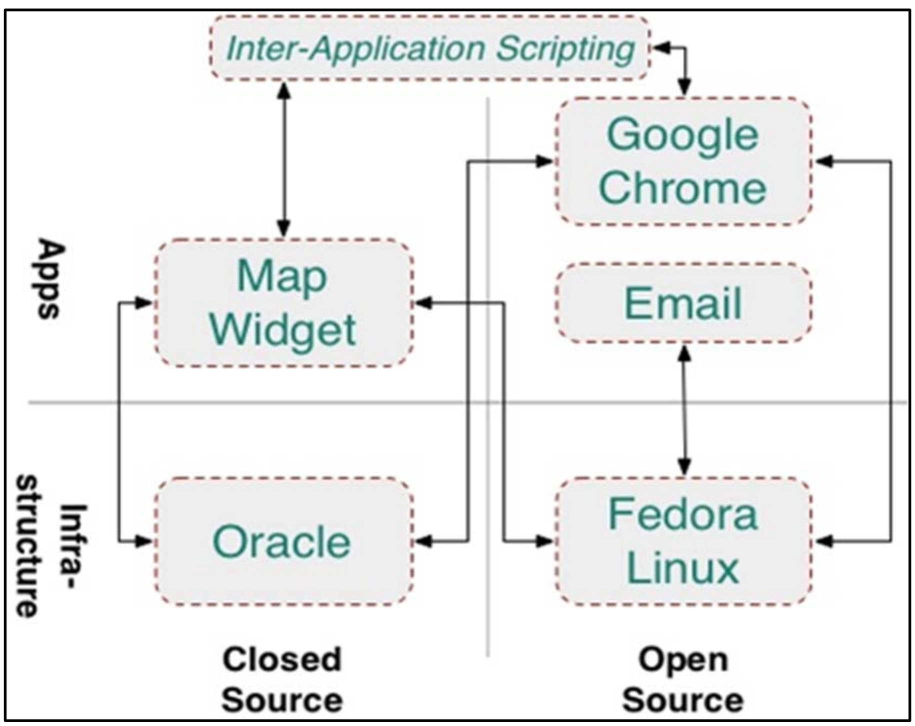

Figure 6. A Selection of Software Components From the Ecosystem in Figure 4 Conforming to the OA System Design in Figure 5

Lightweight software widgets are developed using domain-specific scripting languages, like JavaScript or PHP, which are designed to operate with popular Web

browsers or browser-based integrated system environments. These widgets commonly represent small programs that are often produced with limited resources on short time frames and sometimes constitute only hundreds of lines of scripting source code. More complex integrated capabilities can be constructed by integrating a set of selected widgets using additional scripting code via integration techniques that produce inter-application "mashups." Consequently, there is substantial competition in the widget/app marketplace. However, these lightweight software components often have short-term life cycles, and few updates before their demise.

At present, lightweight software components tend not to be sustained for periods beyond their early availability, widespread adoption, and deployment. Their life cycle may be measured in months, rather than years (or decades). Consequently, these lightweight components are effectively designed to be disposable, low-cost software—acquire it, then use it until something better is available, then repeat. This means that it may be easier for producers of such components to develop new components with new(er) capabilities, technologies, or remote services, rather than trying to sustain the short-lived legacy code. In this regard, producing new components may be less costly than maintaining legacy components that depend on technologies or services that may no longer be available or viable. Lightweight software components with short life cycles in this regard may improve competition, overall system adaptability, and affordability while reducing vendor lock-in to costly legacy software. Updated versions of such components may be provided to repair or replace problematic implementations, but they may also appear simply as an inducement to maintain use of the component until an extended (e.g., "pro") version becomes available for acquisition. Finally, the globally dominant online app stores like those operated by Apple, Blackberry, Google, Microsoft, and others tend to primarily/exclusively distribute small, lightweight software components as proprietary closed source executables on a per-user basis, and with IP licenses that prohibit open access, reuse, modification, and redistribution. But these choices are determined by the business models of the online repository/store operators, rather than on some critical technological dependency or constraint. So new software products like lightweight components from online repositories/stores will likely require more agile acquisition processes, contracting practices, and replacement/upgrade and IP license management regimes.

In contrast, the Web browsers in which these widgets run are themselves substantial multi-million source lines of code software components that are often integrated into larger software-intensive defense systems, like the C2RPC experimentation platform (Garcia, 2010; Gizzi, 2011). These browsers and other integrated software packages are tested and deployed on global scales, which in turn helps to insure their viability, sustainability, and quality within a highly competitive software product ecosystem. Their availability as either proprietary or OSS forms indicates that there is active, ongoing competition among their producers. In addition, these OSS browsers and other integrated software packages based on open standards (e.g., OpenOffice, LibreOffice) mean that commonly used, large-scale software applications and software infrastructure systems are available with IP licenses that offer lower acquisition costs and improved competition, as well as improved defense affordability options.

OSS components found at SourceForge.net or Forge.mil are typically somewhere in between in size, complexity, and functional capability of lightweight widgets and large integrated software packages. However, there is no requirement imposed in OSS repositories about what size, complexity, or capability components can be made available. So many OSS components range in size from thousands to hundreds of thousands of source lines of code, and they vary in terms of their quality and sustainability. OSS

components from online repositories like SourceForge.net are generally available for free or for a low cost and may or may not be designed around open standards. Many OSS-based applications do not rely on any standards, while much OSS-based infrastructure software relies on either open industry standards or de facto standards grounded in proprietary/legacy systems (sometimes referred to as "workalike" or functionally similar [Scacchi & Alspaugh, 2012b] systems). In contrast, the DoD is seeking to make sure that its online OSS repositories like Forge.mil (or others) will only host components that are pre-tested and certified as compliant with relevant standards, quality/reliability indicators, and security policies relevant to their problem domain (DISA, 2012; Kenyon, 2012; Reed et al., 2012].

Software components and online component repositories/stores offer the potential to transform the ways and means for acquiring and developing component-based OA systems. But at present, the size, functional complexity, quality, extensibility, and sustainability of different software components vary in part based on the repository/store from which they are acquired. Although components that can be integrated within a secure OA system offer the potential to increase competition, the acquisition processes need to be updated and the acquisition workforce newly trained in these new ways and means in order to maximize the likelihood for BBP initiatives addressing OA systems.

How Best to Improve and Streamline Acquisition Processes for Secure Open Architecture Systems

The transition to the development, deployment, and sustainment of software-intensive systems based on an OA means that new or revised acquisition processes may be needed. In particular, we believe that such advances call for (a) the adoption of open business models within the DoD and its industry partners, (b) open source approaches to creating Web-based acquisition processes (Scacchi, 2001) that specifically address BBP initiatives, and (c) employing techniques for streamlining these processes (Choi & Scacchi, 2001; Nissen, 1998; Scacchi & Noll, 1997; Scacchi, 2001) for secure OA systems. Each is described in turn in this section.

Encouraging the Adoption of Open (Source) Business Models

One goal of BBP initiatives is to reduce costs by improving competition. Such a situation may be disconcerting to legacy software producers who are long experienced with the long-term development of proprietary, large-scale software systems with closed architectures that are subject to traditional, cumbersome, and costly software product licenses and license management regimes (Anderson, 2012; Konary, 2009). A move towards the agile and adaptive development of secure OA systems based on software components—that can be developed/integrated more rapidly and at a lower cost with more favorable IP licenses—represents a new acquisition strategy (Reed et al., 2012; Scacchi & Alspaugh, 2013b). This suggests the need to incentivize software producers and system integrators so as to insure their ability to effectively produce both proprietary and OSS components that are economically viable yet cost effective to the government over the life of such systems. The overall BBP mandate recognizes this situation but does not specify the means for how best to accomplish it. We believe that one promising candidate is for defense enterprises and program offices to adopt new open business models.

The business models that we have in mind should be rendered in an open source format. Such models should be computer processable (i.e., amenable to automated enactment support) and transparent to participants in the acquisition workforce (e.g., available through Web-based application systems [Scacchi, 2001; Scacchi & Noll, 1997]). They should similarly be open to participants in software producer, system integrator, and

system user enterprises. These models should incorporate a product line of common/reusable open system architectures that can integrate functionally similar software components in order to realize domain-specific system solutions (e.g., for domains like C2, weapon systems, or enterprise computing; Bergey & Jones, 2010; Guertin & Clements, 2010; Jones & Bergey, 2011; Reed et al., 2012; Scacchi & Alspaugh, 2012b; Northrop & Clements, 2007; Womble et al., 2011). These business models should incorporate Web-based computational models of acquisition processes (Nissen, 1998; Scacchi, 2001; Scacchi & Noll, 1997) that manage the system development and support processes that surround the OA product line system models. Finally, these business models should highlight which acquisition or system development processes, or OA system features, require attention to IP licenses.

Prior research has demonstrated that significant cost reductions and process streamlining are possible when open source business process models are utilized (Choi & Scacchi, 2001; Nissen, 1998; Scacchi & Noll, 1997; Scacchi, 2001). These kinds of models can be subjected to performance measurements across multiple acquisition process enactments, continuous improvement, and process redesign by the acquisition workforce (Scacchi, 2001). Now we propose to enhance and extend their value through the incorporation of OA system models. While demonstrating such a capability is beyond the scope of this study, prior research results suggest the plausibility of such an approach. So future acquisition research targeting BBP may be directed to the creation of open business models that can be openly accessed, reused, modified, and redistributed where appropriate.

Open Source Models of Acquisition Processes

As noted, prior research has demonstrated the value and real payoffs of Web-based computational models for defense acquisition processes (Choi & Scacchi, 2001; Nissen, 1998; Scacchi & Noll, 1997; Scacchi, 2001). However, many technological advances, organizational transformations, and shifting defense priorities have occurred since these results were first demonstrated and deployed years ago. Our own studies on the design of secure OA system product lines are an example of technological advances not addressed in our earlier process models. But without explicit, open source process models that can be enacted through Web-based user interfaces (i.e., Web browsers accessing remote application services while tracking process enactment progress and performance parameters), the ability to realize their benefits (like process streamlining and cost reduction) is elusive and difficult to manifest. Among the reasons for why this is so includes overcoming gaps for how best to (a) monitor and measure acquisition process performance without automated enactment support; (b) redesign legacy processes to better accommodate technical advances and to remove ineffective bureaucratic procedures, or that transform acquisition processes in ways that do more with less while also empowering the acquisition workforce; (c) design new acquisition processes like those for acquiring secure, component-based OA software systems subject to multiple IP licenses; and (d) accommodate software IP licenses and license management regimes as acquisition process cost elements. To better understand what gaps exist in these four areas, we now describe techniques for streamlining the acquisition processes for secure OA systems.

Techniques for Streamlining Acquisition Processes for Secure Open Architecture Systems

A goal of this paper is to identify ways and means for streamlining acquisition processes for secure OA systems. In particular, we focus on four kinds of techniques that can be used to streamline such processes in ways that are responsive to the BBP initiative for open system architectures subject to complex IP licenses. These techniques are

illustrative rather than exhaustive since other kinds of techniques in other areas are also expected to exist and be available for practice by the acquisition workforce.

Process Measurement and Assessment

The most direct way to determine the efficiency and effectiveness of acquisition processes is by measuring their structural attributes. Such attributes indicate things such as (a) the length of the longest path of process steps/actions (process length); (b) the number of distinct process paths (process width); (c) the number of sub-process levels (process depth); (d) the total number of process steps (process size); and (e) the process size divided by process length (process parallelism) as well as others metrics (Nissen, 1998). But without an explicit graph-based model of acquisition processes, such measurements are impractical or implausible. Nonetheless, such metrics are a key for where to look for process improvement or process redesign opportunities. One might also recognize that some acquisition processes are underspecified—for example, by not explicitly accounting for where software licenses are negotiated or license trade-off analysis is done. Similarly, because OA systems may include software components subject to different licenses (Alspaugh et al., 2010), how are component-component license interactions assessed or analyzed, if at all? If acquisition processes do not explicitly account for new acquisition or license management activities that emerge due to advances in OA system development, then such processes are underspecified, which means their costs are hidden and difficult to control/minimize. Thus, if the goal of BBP is to help improve the affordability of OA systems within the DoD, then we need to be able to systematically model, measure, and assess our acquisition processes (Scacchi, 2001). Similarly, we need to better understand how to measure and assess open business models for use within the DoD and its industry partners to incentivize and continuously improve competition and defense affordability

Process Redesign and Evolution

Once we have the ability to measure and assess current/emerging acquisition processes for secure component-based OA systems, we can then begin to analyze (or simulate) them in ways that reveal process redesign opportunities and transformation heuristics (Choi & Scacchi, 2001; Nissen, 1998; Scacchi & Noll, 1997; Scacchi, 2001). Among the acquisition process pathologies we seek to identify are those where measured processes reveal sub-processes with low effectiveness (indicating high levels of iterative rework), low efficiency (indicating slow or bureaucratically cumbersome process steps that add marginal value to process completion), and problematic sub-processes (indicating underspecified process steps, steps that generate processing delays due to missing and/or incorrect acquisition data, or inappropriate automated process enactment support). For example, current processes that assume the long-term acquisition of monolithic software systems with proprietary components integrated within a closed architecture are likely not well suited to address the challenges for acquiring secure OA systems that integrate software components from different online repositories. We also place our acquisition workforce at a disadvantage if we do not empower them with the ability to measure, assess, and adaptively redesign their processes as technological advances like component-based OA systems are to be acquired. New software component technologies and software ecosystem niches (Scacchi & Alspaugh, 2012a) are also emerging, which necessitate new continuous development processes and new license management practices and thus the redesign/evolution of acquisition processes (Scacchi & Alspaugh, 2013a; Scacci et al., 2012). These examples all point to new opportunities to redesign, evolve, or otherwise transform existing acquisition processes to better fit the challenges posed by the development, deployment, and support of secure, component-based OA systems. Finally, we can empower the acquisition workforce to realize continuously improved acquisition

processes if we can provide them with the training and resources for modeling, analyzing, and redesigning their acquisition processes in ways that utilize Web-based automated process enactment systems, which also allow them to try out and walk through alternative process redesigns before committing to their use in daily operations.

Design New Acquisition Processes

Across the DoD community, there are many variations in practice for how to specify and model the architecture of a software-intensive system. Some practices focus attention primarily on identification of major components or abstract layers while minimizing (or ignoring) attention to interfaces and interconnections, which are more challenging to identify and manage. However, the BBP initiative for OA systems points to the need for managing explicit interface specifications that identify and reinforce the use of standard interfaces (DAU, 2012). Without such interface and interconnection specifications, it is not possible to determine the scope or potential conflicts/matches between the IP licenses (and thus TD rights) for the overall system architecture. In contrast, we have demonstrated in our prior research that component-based OA systems become tractable and evolvable from IP license management and security perspectives when the system architecture of components, connectors, and interfaces are explicitly modeled (Alspaugh et al., 2010; Scacchi & Alspaugh, 2011, 2012a, 2012b, 2013b). The use of standard interfaces further allows for simpler renderings of OA system structure, and thus simplifies license analysis. Further, once interfaces and interconnections become explicit, software component producers, system integrators, and/or system consumers can determine/negotiate which interfaces should be standardized in order to improve competition and affordability. These standards may then define acceptable data types, relationships between data types, data attribute value ranges, and exceptional data values in ways that are open, sharable, and reusable as well as extensible when appropriate. Such improvements become possible by enabling an agile, adaptive ecosystem for software components of different size and capability relative to OA system product lines for different application domains (Reed et al., 2012; Scacchi & Alspaugh, 2012a, 2013b). Therefore, another important technique for streamlining the acquisition of secure, component-based OA systems, in line with BBP initiatives, is to provide the acquisition workforce with the resources and automated support to design and computationally enact new acquisition processes (i.e., explicitly modeled processes; Choi & Scacchi, 2001; Nissen, 1998; Scacchi & Noll, 1997; Scacchi, 2001), where the processes are open, agile, and adaptive. Such modeled processes may also then be shared, reused, continuously improved, and redistributed across the ecosystem of defense enterprises and program offices.

Cost Management as a Process Design Element

Part of the promise of the move to OA systems stems from their perceived potential to reduce acquisition life cycle costs, improve competition, and improve defense affordability (DAU, 2012). But where and how are the associated cost factors or cost drivers for OA systems identified, tracked, and managed? After all, if we do not know where the cost factors are, or what activities, conditions, or events drive OA system acquisition costs, then we cannot effectively control such costs nor make well-informed system capability/cost trade-offs. For example, people who manage the acquisition of large-scale software systems within various defense enterprises are familiar with the many types of end-user license agreements for proprietary, closed source software systems (Anderson, 2012). In contrast, these people may not know how best to manage the acquisition of OA systems whose software components are jointly subject to different OSS or proprietary licenses.

The acquisition workforce have also learned in practice that software IP licenses are subject to change over time. However, one consequence is that long-lived or widely used

software systems become more costly and much less amenable to technology substitution or vendor replacement, thereby reducing competition due to vendor lock-in. This works against defense affordability. In contrast, emerging online repositories offer different kinds of software components with different functional capabilities (described earlier) along with different IP licenses and end-user licenses (e.g., low-cost, per-user licenses). These repositories of software components represent a means for increased competition and affordability but are subject to different acquisition, development, or integration processes that are just coming to light. Accordingly, we believe that streamlining the acquisition process for secure, component-based OA systems requires that IP license cost obligations (e.g., license fees for end-user agreements) and license management regimes need to be incorporated into process measurement and assessment, process redesign and evolution, and the design of new acquisition processes. This is also a subject for further acquisition research—but one offering practical near-term consequences.

Conclusions

In this paper, we presented our current results from an ongoing investigation of how best to acquire secure OA software systems. These systems incorporate SPL practices that include closed source proprietary software and OSS components, where such components and overall system configurations are subject to different security requirements. The combination of SPLs and OSS components within secure OA systems represents a significant opportunity for reducing the acquisition costs of software-intensive systems by the DoD and other government agencies. Through our research efforts, we seek to make the acquisition of secure, component-based OA systems a simpler, more transparent, and more tractable process. Such a process must be easy to explicitly model, share, reuse, adapt, and streamline for different system application domains. Our goal was to identify ways and means for how to realize cost reductions and improve acquisition workforce capabilities in ways that address BBP initiatives associated with the move to OA systems and licenses (DAU, 2012).

In this paper, we identified different ways and means for how to streamline the acquisition process for secure OA software systems through a focus on doing more with limited resources. Central to our approach was our effort to identify and characterize new ways and means for acquisition process measurement and assessment, process redesign and evolution, the design of new acquisition processes, and the incorporation of cost factors and cost drivers as an element in new acquisition processes. Along the way, we paid particular attention to revealing how licensing practices for emerging online software component marketplaces can affect cost in ways that either hamper or better the buying power of acquisition programs. Consequently, we sought to identify possible next steps for new acquisition research that can further accelerate efforts to improve competition and defense affordability as well as empower the acquisition workforce going forward, in ways aligned with BBP initiatives.

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System of Systems Management

Acquisition Management for System of Systems: Affordability Through Effective Portfolio Management

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Identifying Governance Best Practices in Systems-of-Systems Acquisition

David J. Berteau, Guy Ben-Ari, Joshua Archer, and Sneha Raghavan
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The Making of a DoD Acquisition Lead System Integrator (LSI)

Paul Montgomery, Ron Carlson, and John Quartuccio
Naval Postgraduate School

Innovating Naval Business Using a War Game

Nickolas Guertin and Brian Womble*, United States Navy*
Paul Bruhns, *ManTech International Corporation*

Computer-Aided Process and Tools for Mobile Software Acquisition

Christopher Bonine, Man-Tak Shing, and Thomas W. Otani
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Acquisition Management for System of Systems: Affordability Through Effective Portfolio Management

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Abstract

The lack of focus on complexity issues in System of Systems–related acquisitions prevents effective support for Better Buying Power (BBP) targets of affordability, innovation, increased productivity, and healthy competition in reducing costs and improving delivery of promised performance. The impetus is to provide the necessary analytical frameworks and associated tools that enable better informed decisions in support of BBP objectives. This paper extends our previous work in robust portfolio optimization and adopts a multi-period portfolio management approach to support the objectives of BBP. Derived from the financial engineering and operations research literature, robust multi-period portfolio management principles provide a decision-making framework that balances performance of a "portfolio" of systems, constituting, for example, a system of systems, against potential risks. The framework also balances short versus long term gains through its multi-period formulation. An illustrative example, using a Littoral Combat Ship–inspired naval warfare scenario, demonstrates application of the approach and potential use for acquisition practitioners.

Introduction

The U.S. Department of Defense (DoD) has emphasized a need for Better Buying Power (BBP) initiatives in tackling issues of increasing costs, schedule growth, and reduced productivity. The success of BBP policies in reducing costs have been well documented for a variety of cases that include the acquisition of Navy destroyers, reduction in production rates for the E-2D Hawkeye program, and cutting cycle times and cost of ammunitions through an improved small business acquisition strategy. However, the complexities of modern platforms that interact as a *system of systems* (SoS; Maier, 1998) present the risk of cascading modes of failure; this is due to the highly interdependent, yet operationally and managerially independent, interactions between the constituent systems. The desire to promote adequate competitions and growth of technological options in developing military capabilities has further increased the complexity of the acquisition process. This increase in complexity now includes the need to account for competitive elements in contracting, improving productivity, and reducing unnecessary redundancies. The management of Major Defense Acquisition Programs (MDAPs) through a "should cost–will cost" imperative becomes increasingly difficult as acquisition decisions must carefully balance performance and risk, and time.

The acquisition of systems with an SoS capability in mind increases the complexity. Current tools especially for this problem context are lacking. Figure 1 shows an abstraction

of the hierarchical and complex relationships among the individual layers of systems in satisfying requirements and consequently, desired overarching SoS level capabilities.

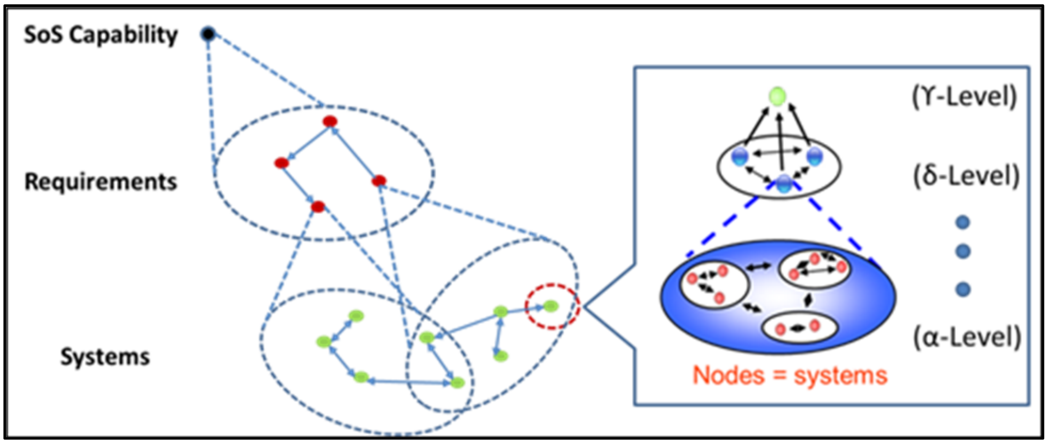

Figure 1. System of Systems Hierarchy

The DoD (2012) *Defense Acquisition Guidebook* (DAG) and DoD System of Systems SE guide provides fundamental guidance in tackling SoS-related acquisitions; however, these greatly lack the necessary depth and decision tools in support of BBP objectives. The lack of an effective decision support framework for managing acquisition risks has led to cascading cost overruns, schedule delays, and even program cancellations. Examples of these effects have been observed in several programs such as the Joint Strike Fighter, U.S. Army Future Combat Systems (FCS; Gilmore, 2006), and U.S. Navy Littoral Combat Ship (LCS; O'Rourke, 2011) programs. Computational decision support frameworks are needed to adequately deal with the complexity of interconnected acquisition domains and to identify optimal collections of systems that mitigate cascading risks.

Investment Portfolio Management: A Path to Better Buying Power

Portfolio management techniques have been successfully applied to the management of strategic "portfolios of systems" in military acquisitions; this includes application of Real Options (RO) theory and metrics such as *Knowledge-Value Added* (KVA) that account for the value added by human and IT investments (Komorovski, Housel, Hom, & Mun, 2006). Work by Mun (2005) has developed an eight-phase process to addressing portfolio management of strategic assets. Work by Giachetti (2012) has applied stochastic techniques to managing military investments. Previous research funded by the Naval Postgraduate School (NPS) and presented at the 2012 NPS Acquisition Research Symposium (Davendralingam, Mane, & DeLaurentis, 2012), has focused on a robust portfolio management problem of maximizing a warfighter SoS portfolio performance index while preserving budgetary and compatibility constraints of underlying military assets. The robust portfolio work complements prior research efforts to include algorithmic advances, explicit consideration of data uncertainty, and inclusion of SoS architectural information within a robust investment portfolio framework. The robust portfolio methodology is adapted from financial engineering literature and leverages potential gains in overall SoS capability against cost and developmental risks in selecting "baskets" of compatible, interdependent systems.

Risks and capabilities associated with system interdependencies can span the functional or physical spaces of the SoS construct and is subject to uncertainty. The developed strategy supports acquisitions, both in the pre- and post-milestone B phases, and considers current initiatives such as open architecture (OA) and competitive contracting

(e.g., fixed-price initiatives) in improving affordability and BBP objectives while considering evolving military requirements. Work in this research extends the robust portfolio approach to include a multi-period portfolio perspective. The multi-period portfolio optimization approach draws upon a rich history of algorithmic development, as noted in operations research–related literature (Powell, 2011; Bertsimas & Pachamanova, 2008; Bertsekas, 2005; Fabozzi, Kolm, Pachamanova, & Focardi, 2007; Tutuncu & Cornuejols, 2007). Its roots stem from *sequential decision-making* areas known broadly as *dynamic programming* or stochastic programming and adapts control theory methodologies to the dynamic management of resources in the interest of maximizing (or minimizing) some given metric. *Stochastic programming* focuses on issues of uncertainty whereas dynamic programming relates to the optimality of making sequential decisions; however, there has been a large degree of overlap and exchange between the two areas. Algorithmic development in these areas has been applied to a range of real-world dynamic decision-making problems that range from financial portfolio management to real-time control of vehicles.

A Multi-Period Decision-Making Framework

The multi-period portfolio approach enhances the robust portfolio decision-support framework and better enables optimal acquisitions of systems in maximizing SoS-wide capabilities. The construction of an appropriate dynamic policy, in the context of an acquisition management problem, translates to identifying actions that balance the potential gains in SoS capabilities against developmental risks (e.g., cost and schedule growth risks) over a specified time horizon. Figure 2 is an abstraction of the evolution of a “portfolio of systems” that constitute an SoS, as part of the wave model (Dahmann, Rebovich, Lane, Lowry, & Baldwin, 2011).

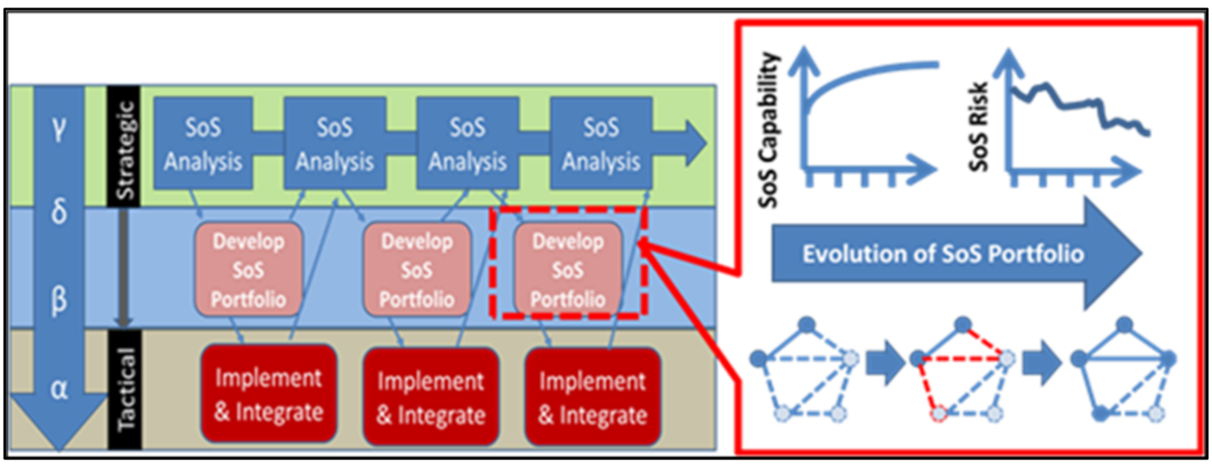

Figure 2. Wave Model Relation to Portfolio Evolution

The wave model is an extension of the Department of Defense guidelines on systems engineering (SE) for an SoS that translates SoS SE core elements, interrelationships, and decision-making artifacts from a previous “Trapeze” model to a time-sequenced model representation (Dahmann et al., 2011). These architectural decisions involve the acquisition of assets in evolving the SoS capabilities to meet core objectives; the SoSE architect’s role is to explore the trade space across multiple operationally independent domains in determining suggested architectural modifications (add/remove assets) in evolving the SoS.

A Multi-Period Decision Framework

The objective of the robust multi-period portfolio framework is to allow for mathematical rigor of algorithmic techniques, transparent to the end user/practitioner, to support SoS-level acquisition decisions through identification of optimal “portfolios” of systems to be acquired in pursuit of desired SoS capabilities. While the acquisition process spans operationally and managerially independent defense groups, the tools and frameworks envisioned to support these aspects are aimed at providing adequate trade space exploration capabilities. These explorations require a domain agnostic framework, and hence intuitively resonate with the idea of treating the collection of systems across domains as a “portfolio” of systems in the SoS.

This is often the case in operations research and financial engineering applications, where underlying mathematical optimization frameworks are used to drive decision support software in assisting decision-makers (e.g., policymakers, investment specialists) in performing acquisition analysis. The concept naval warfare scenario in this paper demonstrates the application of the multi-period portfolio framework in managing the sequential acquisitions needed to propagate required capabilities while minimizing operational and developmental risks. The method illustrates the identification of optimal evolution of interconnected systems that cohesively function in providing an overarching SoS-wide capability. A robust optimization approach to the multi-period portfolio formulation addresses issues of data uncertainty.

Development of a Multi-Period Investment Portfolio Model

The acquisition (and removal) of systems in an evolving an SoS inherently involves a timeline of sequentially executed decisions. Decisions made at each epoch affect the decision options of future states, thus affecting long term performance and risks of the SoS gamut. The translation of these sequential decisions to the context of a multi-period investment model requires an adequate description of node (system) attributes; this ensures the selection of feasible portfolios that satisfy nodal requirements and minimize cascading risks. Figure 3 shows modeled generic behaviors for systems being considered in an SoS portfolio.

System-of-Systems Modeling

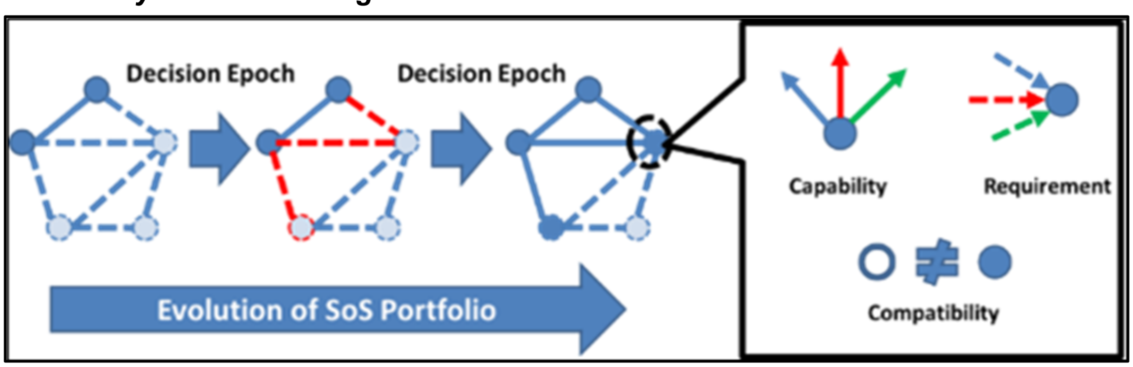

Figure 3. Archetypal Node (System) Behaviors

In Figure 3, the capabilities of an existing SoS (initial blue nodes) have the potential to evolve, based on potential connections to yet-to-be acquired systems (dashed lines and nodes). At each decision epoch, the practitioner utilizes a decision-making framework (such as the multi-period portfolio framework) to evaluate the value and risks involved in the potential acquisitions of new systems (denoted by red dashed lines). The resulting new

collection of systems that comprise the new SoS construct now includes the addition of the new systems.

An SoS is treated as a set of generic discrete nodes with the following attributes:

- *Capability (Outputs)*: Nodes have finite supply of capabilities that are limited by quantity (e.g., total power output of generator systems).
- *Requirements (Inputs):* Nodes have individual requirements. Requirements are fulfilled by receiving capabilities from other nodes that can fulfill said set of requirements (e.g., a high powered AMDS radar requirement of energy can be fulfilled by multiple generators).
- *Compatibility:* Nodes can only connect to other nodes based on a pre-established set of rules (e.g., AMDS radar can only accept power from high capacity nuclear reactor systems on specific ships).

Multi-Period Investment Portfolio Formulation

The problem statement for a multi-period investment portfolio is translated to the language of mathematical programming. The process begins with the definition of two main elements of a mathematical program, namely, the *objective function* and *constraints*. The objective function is a mathematical expression that is formulated to reflect a key performance metric of the system to be maximized (or minimized). Typical formulations of the objective function seek, for example, to minimize direct costs of operating a fleet of aircraft. For an SoS, the objective function reflects a chosen measure of performance and associated costs. The second important aspect of a mathematical program is the formulation of the constraints. The constraints reflect physical, resource, and behavioral aspects of the systems as mathematical expressions. Our initial framework for a multi-period portfolio considers a long term horizon of acquisitions with discrete decision steps that denote periods of “investment”; these investments involve the addition/removal of individual systems that comprise the overall SoS network.

The following mathematical program describes a preliminary framework for the multi-period acquisition problem:

$$\max\left(\sum_{q}\left(\frac{S_{qc}-R_c}{R_c}\cdot w\cdot X_{q=T}^{B}\right)\right) \quad (1)$$

subject to:

$$X_{q,t}^{B}=X_{q,t-1}^{B}+U_{q,t}^{B}+V_{q,t}^{B} \quad (2)$$

$$C_t^{trans}=C_q^{B}U_{q,t}^{B}+C_q^{S}\,V_{q,t}^{S} \quad (3)$$

$$\sum_{t=0}^{T}C_t^{trans}\leq \text{Budget} \quad (4)$$

$$\sum_{q}S_{qtC}\,X_{q,t}^{B}\geq\sum_{q}S_{qtR}\;X_{q,t}^{B}\ \text{(Satisfy Requirements at each t)} \quad (5)$$

$$\left(X_{i,t}^{B}+..+X_{n,t}^{B}\right)_{j,t} = M_{j,t}\ j = 1 \ldots k \text{ (Package System Compatibility) (6)}$$

$$X_{q,t}^{B}, X_{q,t-1}^{B}, U_{q,t}^{B}, V_{q,t}^{B}\ \epsilon\ [0,1] \text{ t=0…T (time steps)} \quad (7)$$

where:

w - weighting factor vector that weights the importance of constituent capabilities of index

R_c - baseline capability level for each of the capabilities that contribute to index

$C_{q,t}^{B}$ - cost of acquiring system (q) at time (t)

C_t^S -cost of retiring system (q) at time (t)

Equation 1 is the weighted objective function that seeks to maximize the end developed SoS performance index. Here, the index is related to the final state of the portfolio ($t = T$) and is weighted according to the value that each capability (C) contributes to the index (however, this can naturally reflect maximization of each stage, if necessary). The index is normalized by referencing it to some chosen reference capability set (R_c). Equation 2 reflects the evolutionary nature of the portfolio of chosen systems (q) at time (t), represented by the decision vector $X_{q,t}^{B}$. Here, the decision vector is binary, to reflect discrete system choices; however, a more general setting can allow for the variables to be continuous in nature.

The terms $U_{q,t}^{B}$, and $V_{q,t}^{B}$ reflect decisions to "acquire" and "remove/retire" individual systems respectively, in the portfolio of systems at each decision epoch of time (t). Equation 3 captures the "transactional" costs at each stage; this means that decisions to acquire/remove systems translate to costs associated with each that are accrued at each time step. In acquisitions, the removal cost translates to a salvage/swap cost for changing out individual systems whereas the "acquire" cost is simply the cost of purchasing and integrating a new system. Equation 4 ensures budgetary balance for total costs (transactional and acquisition) that occur.

Equation 5 ensures that the total "capabilities" from systems acquired satisfy the requirements that individual systems may have; for example, there must be adequate power generating systems selected to support selected communications systems that provide some system-wide communications capability. Conditions for Equation 5 can be enforced at each time step (t) or at the final stage ($t = T$), depending on requirements at each time step. Equation 6 enforces compatibility constraints as binary conditions for a total of (k) set of rules; for example, the constraint that only one engine can be selected to generate power would translate to a constraint of $x_1 + x_2 = 1$ where ($x1, x2$) are binary variables. The rules can be applied across decision epochs, reflecting the need to have prior systems in existence, before particular upgrades can be implemented in future time steps. Equation 7 states that the decision variables are binary and that the time window consists of discrete steps from $t = 0$ to a final time $t = T$. The problem formulation of Equations 1–7 constitutes a *binary integer program*, for which efficient methods of solution and commercial solvers are available.

Robust Multi-Period Investment Portfolio

The multi-period formulation of Equations 1–7 are deterministic and do not consider uncertainties in the data. Real world systems are inherently driven by uncertainty and thus challenge the optimality (and feasibility) of decisions made under deterministic assumptions.

Research in mathematical programming has progressively focused more on the development of robust optimization methods to deal with manifestations of uncertainty. Robust optimization seeks to find solutions, to uncertain mathematical programming problems, that are less sensitive to parametric variations in the problem being solved. We consider uncertainties in the data for Equations 1–7, namely in the "transaction costs" of Equations 3 and 4 that reflect system addition and removal costs. We also consider uncertainties in the capabilities of each system available.

The consideration of the uncertainty in the multi-period formulation requires the use of robust optimization methods for solution. There are a range of methods that can address the uncertain linear structure of the resulting optimization problem; however, we adopt the Bertsimas–Sim (correlated case) approach for our preliminary multi-period framework. The Bertsimas–Sim method (Bertsimas & Sim, 2004) is a robust optimization approach to solving linear optimization problems with uncertain data. The method allows for a flexible adjustment in the level of conservatism of the robust solutions (termed the *Price of Robustness*) in terms of probabilistic bounds of constraint violations.

We consider the following to be a general uncertain linear program:

$$\text{maximize } c^T x \tag{8}$$

subject to:

$$A_X \leq b \tag{9}$$

$$x \geq 0 \tag{10}$$

Where values aij of matrix A are uncertain and exist in the nominally symmetric bounds of $[a_{ij} - a_{ij}, a_{ij} + a_{ij}]$. The uncertainties are treated as *constraint-wise* uncertainties. In the correlated case, the uncertainties are modelled as the following equation:

$$\bar{a}_{ij} = a_{ij} + \sum_{k\epsilon\, K_i} \overline{\eta}_{ik}\, g_{kj} \tag{11}$$

where $\overline{\eta}_{ik}$are the independent and symmetric random variables [-1, 1], and there are k number of uncertain sources. The robust optimization problem to the correlated case can be written as the following linear optimization problem (Bertsimas & Sim, 2004):

$$\text{maximize } \; c^T x_j \tag{12}$$

subject to:

$$\sum_j A_{ij} x_j + z_i \Gamma_i + \sum_{j\epsilon\, J_i} p_{ij} \leq b_i \tag{13}$$

$$z_i + p_{ij} \geq y_j \tag{14}$$

$$-y_{j\leq} \sum_{j\epsilon J_i} g_{kj} x_j \leq y_j \tag{15}$$

$$l_j \leq x_j \leq y_j \tag{16}$$

$$p_{ij}, y_{ij}, z_{ij} \geq 0 \tag{17}$$

where p_{ij}, y_{ij}, z_{ij} are the dual variables associated with the dual problem of the nonlinear formulation of the Bertsimas–Sim method (See Bertsimas and Sim [2004] for full derivation), and *J* is the set of uncertain coefficients. The conservatism term, Γ_i, is adjusted to control probabilistic guarantees of constraint (i) violation. For example, changing Γ, for linear constraints that dictates power distribution flow over a network, controls the probability of net power being supplied at a prescribed level of cost. The constraint violation probability bounds for individual constraints can be approximated using the following De Moivre approximation of the binomial distribution (Bertsimas & Sim, 2004):

$$B(n, \Gamma_i) \approx 1 - \Phi\left(\frac{\Gamma_i - 1}{\sqrt{n}}\right) \tag{18}$$

where n is the $\left|J_{i\neg}\right|$ and Φ is the normal cumulative distribution function. The manipulation of Γ in controlling the probability of constraint violation, allows for an intuitive interpretation of the conservatism of solutions generated and permits practitioners the means of assessing solution performances against associated risk in terms of individual constraint violations.

Robustification: Bertsimas–Sim (Correlated) Approach

The robust (correlated) implementation of the Bertsimas–Sim approach in Equations 11–17 is applied to the multi-period model of Equations 1–7. The following equations described the robustified budget constraints for the multi-period model, in particular the context of budget feasibility, expressed earlier in Equation 4:

$$\underbrace{X^B_{q,t=T} + \sum_{t=0}^{T} C_q V^B_{q,t}}_{\prime c^T x_j \prime} + z\Gamma + \sum_{j \epsilon J_i} P_j \leq \text{Budget} \tag{19}$$

$$z_i + p_j \geq y_j \tag{20}$$

$$-y_{j\leq} \sum_{j \epsilon J_i} g_{kj} x_j \leq y_j \tag{21}$$

$$l_j \leq x_j \leq y_j \tag{22}$$

$$p_{ij}, y_{ij}, z_{ij} \geq 0 \tag{23}$$

where x_j is the concatenated decision vector $\left\{X^B_{q,t=T}\ V^B_{q,t=0,1,2}\right\}$ associated with all transactions $(t = 0,1,2)$.

Interpretation of Risk

The inclusion of correlation information reflects an important contribution where protection levels of each robust constraint, in the non-correlated case assumes the simultaneous worst-case scenarios at the uncertainty bounds–a condition that is highly improbable. The correlated case accounts for the simultaneous "movements" in performance and risks across the capabilities of individual assets. Prior research has utilized a mixed integer semidefinite programming (MISDP) approach to dealing with uncertainties in the covariance matrix, a matrix that is associated with variances (risk) in system

development time. However, there are very limited solvers that are able to solve MISDPs, which limits practical implementation, despite some of the computational advantages in dealing with uncertainty.

Concept Application: Naval Acquisition Scenario

The Naval Acquisition Scenario is based on the Littoral Combat Ship (LCS) model (LCS, 2011). The LCS (Figures 4 and 5) is a naval combat vessel, developed by Lockheed Martin and General Dynamics, as a result of the Navy's dual contracting efforts to reduce cost through competition. The design of these ships seeks to provide a more agile and cost-effective solution to various near shore environment missions. These missions are executed through use of interchangeable ship packages that include Mine Warfare (MIW), Anti-Submarine Warfare (ASW), and Surface Warfare (SUW). The highly modular design of the platform allows for a great degree of operational flexibility. The modularity also translates to the ability for *open architecture* and small business initiatives to be brought to bear in reducing program costs and improving competition. Our ongoing work in this paper assumes an LCS-inspired scenario as representative "simple" SoS model where the objective is to identify potential *sequence of investment decisions* and the corresponding end collection of systems that can best maximize core capabilities of the SoS mission (in this case, MIW, ASW, and SUW).

Our highly simplified model consists of a hypothetical list of candidate systems, listed in Table 1, that are available to the Navy for acquisition. Although the numbers presented in the table are fictitious, the salient features of capability, requirements, cost, and uncertainty are nevertheless represented. Each subset of systems (listed by categories of ASW, MCM, SUW, Seaframe, Comm) represents a subset collection of systems that are available in meeting the needs of each category. The ASW, MCM, and SUW categories are the core LCS mission packages. "Seaframe" reflects the ship seaframe support options, and "Communications" represents the support communications systems available for deployment. The first five columns show capabilities of each system, and their respective numerical valuations. Columns 6 and 7 are the *Power* and *Communications* requirements needed for operation of the listed systems, in providing the capabilities listed. Also listed are the acquisition (buy) and retiring (sell/salvage) costs, along with the estimated uncertainty of each cost. We consider uncertainty in costs for this simplified problem; however, more general uncertainty in capabilities or requirements can be introduced in the same fashion.

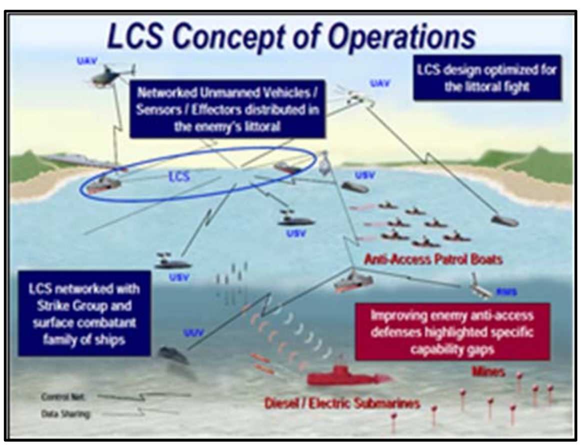

Figure 4. Concept of Operations

Note. Image taken from presentation slides by RDML Vic Guillory of OPNAV at the Mine Warfare Association Conference (titled "Littoral Combat Ship"), May 8, 2007.

Figure 5. General Dynamics Independence Class LCS

Table 1. LCS Candidate System Scenario

Category	System	Weapon Strike Range	Surface Detection Range	Anti Mine Detection Range	Comm Bandwith	Power Bandwith	Power Required	Comm Required	Acquisition Cost	Retiring Cost	Uncertainty Acquisition Cost	Uncertainty Retiring Cost
ASW	Variable Depth	0	50	0	0	0	95	100	1.00E+05	1.00E+05	9.84E+01	3.04E+01
	Multi Fcn Tow	0	40	0	0	0	90	120	2.00E+05	2.00E+05	1.74E+02	1.83E+02
	Lightweight tow	0	30	0	0	0	75	100	3.00E+05	3.00E+05	1.15E+02	2.37E+02
MCM	RAMCS II	0	0	10	0	0	70	120	1.00E+05	1.00E+05	7.80E+01	9.05E+00
	ALMDS (MH-60)	0	0	20	0	0	90	150	2.00E+05	2.00E+05	1.91E+01	1.33E+02
	New Prototype 1	0	0	30	0	0	100	170	3.00E+05	3.00E+05	2.58E+02	1.91E+02
SUW	N-LOS Missiles	25	0	0	0	0	0	250	1.00E+05	1.00E+05	3.49E+01	9.19E+01
	Griffin Missiles	3	0	0	0	0	0	100	2.00E+05	2.00E+05	1.69E+02	8.05E+01
	New Prototype 1	30	0	0	0	0	0	300	3.00E+05	3.00E+05	1.72E+02	2.91E+01
Seaframe	Package System 1	0	0	0	0	300	0	0	1.00E+05	1.00E+05	7.02E+01	4.72E+01
	Package System 2	0	0	0	0	450	0	0	2.00E+05	2.00E+05	1.54E+02	1.42E+02
	Package System 3	0	0	0	0	500	0	0	3.00E+05	3.00E+05	2.41E+02	2.60E+01
Comm.	Comm System 1	0	40	0	180	0	100	0	1.00E+05	1.00E+05	1.26E+01	3.59E+01
	Comm System 2	0	0	0	200	0	120	0	2.00E+05	2.00E+05	1.24E+02	9.83E+01
	Comm System 3	0	0	0	240	0	140	0	3.00E+05	3.00E+05	2.17E+02	7.00E+01
	Comm System 4	0	0	0	300	0	160	0	4.00E+05	4.00E+05	2.20E+02	3.98E+02
	Comm System 5	0	0	0	360	0	180	0	5.00E+05	5.00E+05	7.03E+01	4.15E+02
	Comm System 6	0	0	0	380	0	200	0	6.00E+05	6.00E+05	4.09E+02	4.62E+02

Naval Acquisition Scenario: Results

The problem statement for the above LCS-inspired acquisition problem is formulated as a mathematical program that follows the robustified formulation of Equations 1–7. The resulting problem is then solved for varying values of conservatism, Γ_i, to reflect a range of dynamically evolving acquisitions, at each prescribed level of conservatism. Here, we assume conservatism in dealing with the costs uncertainties of acquisitions; each chosen value of Γ (here, three values) in this context thus reflects the probability of budget overruns occurring due to the associated costs uncertainties in each stage of acquisition. We assume a three-stage (t=0,1,2) acquisition process, where the systems listed in Table 1 can be acquired or retired at each stage, culminating to a final "portfolio" of assets at the end of stage 3 (t=2). Acquisition or retirement of these systems is subject to a prescribed set of rules that govern their compatibility and availabilities in time (systems only available at specific epochs) as reflected in Equation 6 of the problem formulation. Figure 6 shows the SoS performance frontier tradeoff against degree of conservatism in the budget constraint.

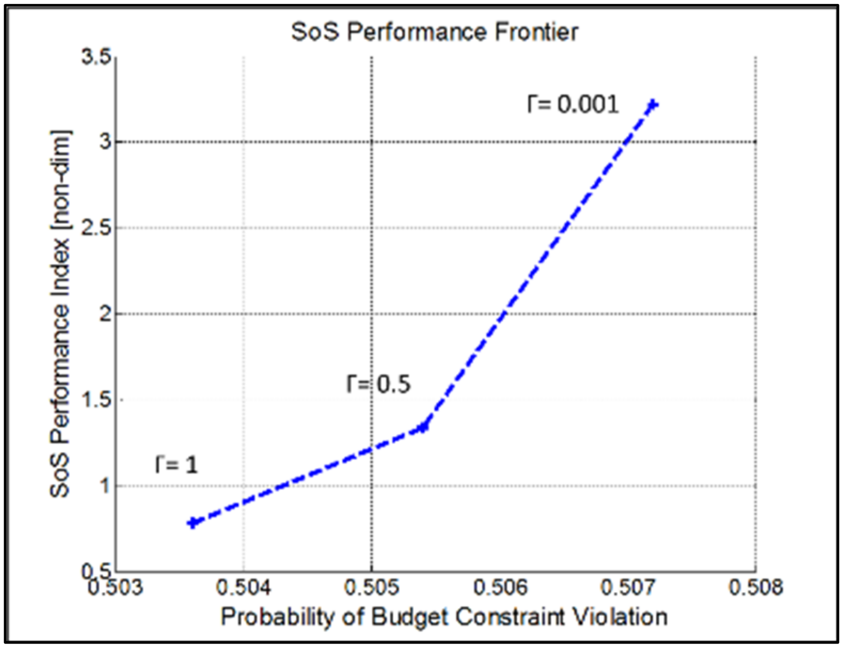

Figure 6. Performance Index Frontier

Figure 6 highlights three dynamic portfolios at conservatism level of Γ = 0.001, 0.5, and 1 respectively; increasing values of Γ indicate a higher degree of conservatism. Each point corresponding to a particular chosen level of conservatism reflects a sequence of acquisition decisions that lead to the final portfolio performance index denoted on the graph. The sequence of acquisitions for each level of conservatism is shown in Table 2, where "1" denotes a decision to acquire a particular system at that time step, t. Figure 7 shows the normalized capability index for each subset of capabilities that comprise the index (in this case, *weapons strike range*, *surface detection range,* and *anti-mine detection range*) of each of the optimal points in Figure 6.

The results in Table 2 indicate evolving portfolio of systems where individual systems are acquired and retired throughout the decision epochs, preserving the satisfaction of requirements, towards maximizing the end goal of the overall SoS portfolio at time $t = T$. Retirements are denoted by the evolution from a previously selected state (e.g., x_{jt}=1 at $t = 2$) to a state of (e.g., $x_{jt} = 0$ at $t = 3$). At a high level of conservatism ($\Gamma = 1.0$), we observe the expected case of the portfolio being constant, where the initial investments are held over the entire decision horizon without any retirement or further acquisitions; this reflects the condition where risks associated with the buy/retire transactions are deemed to be too great, hence prompting the selection of a lower capability but less financially risky acquisition strategy. At the low and mid-levels of conservatism, there is a possibility of sequential acquisitions, subject to the availability and compatibility rules between systems, that can result in higher performing portfolios but at higher prescribed level of acquisition risk.

The results of Table 2 and Figure 7 afford practitioners a candid view of the "topology" of acquisitions that can optimally be made over time, assuming a tolerance of risk for, in this case, and budgetary risk. The risk uses correlated information on the costs and is quantified as the probability associated with the budget constraint violation. The analysis result presented can be useful to decision-makers in assessing the potential dynamic purchasing/retirement decisions that need to be made in view of quantifiable uncertainties. It also allows the decision-maker to assess the trade-offs between performance and risks in

decisions at each epoch of the acquisition process, while bearing independencies and system compatibilities in mind. The mapping of the dynamic acquisition trade-space can also better inform independent acquisition groups, within an SoS, on the potential actions that various collaborative acquisition strategies can have on the overall scheme of development.

Table 2. Portfolio Evolution at Varying Conservatism

System Description	System Package	Γ (Conservatism)								
		0.001			0.5			1		
		t=0	t=1	t=2	t=0	t=1	t=2	t=0	t=1	t=2
ASW	Variable Depth	0	0	0	0	0	1	0	0	0
	Multi Fcn Tow	0	0	0	0	0	0	0	0	0
	Lightweight tow	1	1	1	1	1	0	1	1	1
MCN	RAMCS II	0	0	0	1	0	0	0	0	0
	ALMDS (MH-60)	1	1	1	0	0	0	1	1	1
	New Prototype 1	0	0	0	0	1	1	0	0	0
SUW	N-LOS Missiles	0	1	1	0	0	0	0	0	0
	Griffin Missiles	1	0	0	1	1	1	1	1	1
	New Prototype 1	0	0	0	0	0	0	0	0	0
Seaframe	Package System 1	0	0	0	0	0	0	0	0	0
	Package System 2	1	1	1	1	1	1	1	1	1
	Package System 3	0	0	0	0	0	0	0	0	0
Communications	Comm System 1	1	1	1	1	1	1	1	1	1
	Comm System 2	1	0	0	1	1	1	1	1	1
	Comm System 3	0	0	0	0	0	0	0	0	0
	Comm System 4	0	0	0	0	0	0	0	0	0
	Comm System 5	0	1	1	0	0	0	0	0	0
	Comm System 6	0	0	0	0	0	0	0	0	0

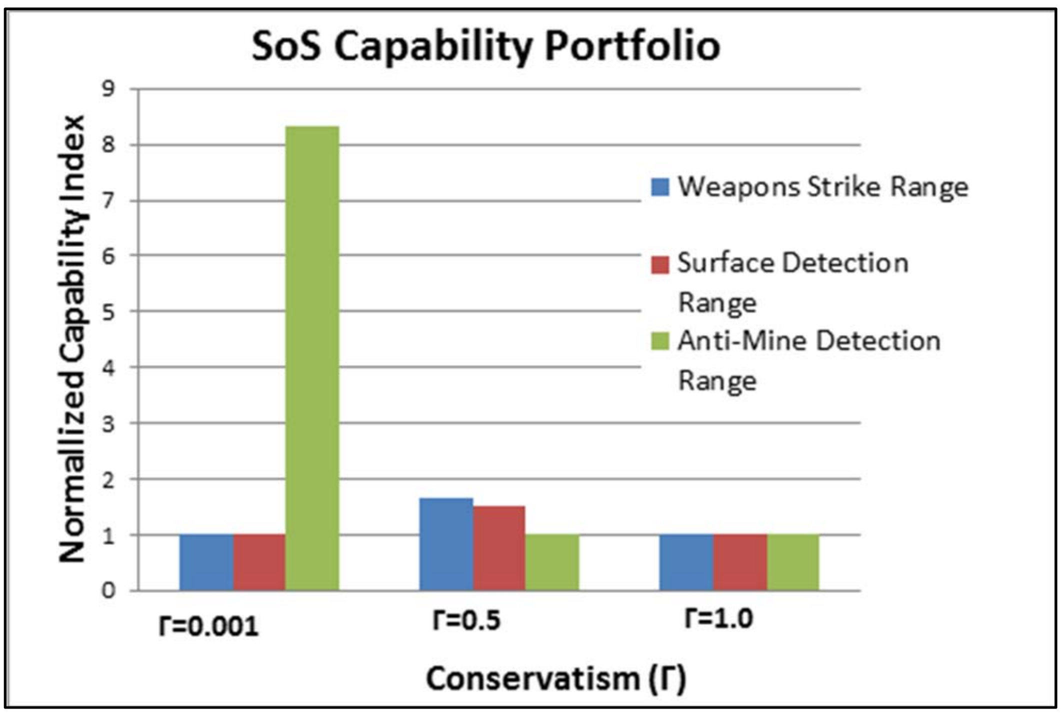

Figure 7. SoS Capability Spread at Varying Conservatism

Conclusions and Future Work

The development of a portfolio of systems to serve in an SoS context is a difficult endeavor. Complex interdependencies and uncertainties abound in both capabilities and requirements of its constituent systems. There is an absence of adequate frameworks and tools to enable effective navigation of the resulting trades-spaces. Research in this paper presents a preliminary framework for a robust multi-period portfolio approach to facilitate selection of systems for acquisition in this context. The framework is naturally based on multi-period portfolio and robust optimization techniques, and it has shown promise in assessing the impact that various degrees of risk aversion (here, conservatism) on acquisition related decision epochs.

The simple LCS-inspired Naval Warfare Scenario demonstrates application of the framework; the objective is to identify optimal acquisition decisions (buy/retire) at each decision epoch, assuming various levels of conservatism in budget violations. The analysis affords practitioners a candid view of the dynamic acquisition trade-space and allows for the selection of systems at the prescribed levels of accepted conservatism. In the larger context of acquisition affordability objectives, the algorithmic framework established here has direct bearing on BBP focus areas, as listed in Table 3.

Table 3. BBP Contributions

Better Buying Power Focus Area	Potential Contribution of Multi-Period Portfolio Approach
Achieve Affordable Programs	• Robust decision-making in a multi-period setting enables mitigation of risks and planning of development steps
Control Lifecycle Costs	• Robust multi-period portfolio accounts for uncertainties in transactional costs at each stage of the decision horizon.
Incentivize Productivity and Innovation & Promote Effective Competition	• Metrics such as KVA and piece-wise linear modeling of incentivizations in a multi-period setting can provide robust management of investments for non-tangible investments and incentivizations • Enables effective management of larger set of acquisition possibilities (e.g., contributions from SBIRs, open architectures)

Our future work will leverage the robust multi-period approach by incorporating relevant metrics and perspectives, as listed in Table 3 above, to more explicitly account for sequential decision-making processes in promoting affordability in defense acquisitions.

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Identifying Governance Best Practices in Systems-of-Systems Acquisition[1]

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Abstract

Acquisition governance currently confronts two problems: the growing size and complexity of systems-of-systems capabilities and the limited effectiveness of existing governance models

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to ensure the on-cost and on-schedule delivery of those capabilities. The Center for Strategic and International Studies (CSIS) is engaging in research on systems-of-systems acquisition governance best practices that could help the defense acquisition community overcome some of these problems. This report provides an update on the progress of that effort. It reviews the evolution of acquisition governance models throughout the history of U.S. defense acquisition, characterizes the ways in which those models fall short of meeting the challenges of complex systems-of-systems acquisition, and offers preliminary observations on best practices to overcome those challenges based on the results of CSIS research to date. That research to date includes two new case studies. The research is continuing beyond this interim report. The final report will reflect additional work and incorporate more case studies.

Introduction

In this age of diverse and evolving security threats, the defense community is acquiring weapons, platforms, and systems with greater complexity. Here, the term *complexity* is used to describe systems-of-systems (SoS) involving multiple, interrelated elements that interact unpredictably. As defense products and capabilities become more complex, they are stressing the structure necessary for the acquisition of defense SoS. As a result, the acquisition community has encountered operational challenges in maintaining a sufficient engineering and acquisition workforce and process, as well as outcome challenges in acquiring capabilities on cost and on schedule.

SoS acquisition poses considerable challenges that the current Department of Defense (DoD) acquisition governance structure was not necessarily designed to address. Increasingly, defense capabilities must support the needs of multiple users and must operate as horizontally integrated systems incorporating multiple individual platforms and programs. The high degree of interoperability and collaboration required for these SoS capabilities necessitates not only advanced systems engineering capabilities but also advanced governance. Because the technical capabilities needed to achieve national defense missions have grown beyond the existing models of governance used to acquire them, the DoD faces challenges in developing, procuring, and deploying next-generation weapons and platforms. Furthermore, cost growth in its portfolio of accounts demonstrates that the DoD is encountering challenges managing cost and schedule risks associated with advanced and integrated capabilities.

The research of the Center for Strategic and International Studies (CSIS) on SoS acquisition governance best practices aims to help the defense acquisition community address some of the challenges of complexity and improve its governance processes for such acquisitions. The specific research covered in this interim report is supported by a grant from the Fleet Logistics Center of the Naval Supply Systems Command, under the auspices of the Acquisition Research Program of the Naval Postgraduate School. The research under this project will conclude with a final report to be submitted in September 2013.

This report focuses on the practical application of the CSIS eight-attribute governance framework in comparative governance model analysis. Specifically, it observes how the attribute profile of two case studies—Future Combat Systems (FCS) and Maritime Domain Awareness (MDA)—has influenced the processes and outcomes of those programs. It outlines the challenges of complexity in SoS acquisition and the historical origins of those challenges. It discusses the eight-attribute framework for the evaluation of individual acquisition programs and applies that framework to the first two example case studies. Finally, it discusses themes indicated by the case study comparison. In the end, this

analysis suggests that getting governance right is critical to addressing the barriers to effective SoS acquisition.

Complexity and Acquisition Governance

The growing complexity of defense systems is not a new challenge to the defense acquisition community. Technology developments in defense have often outpaced the evolution of federal and defense procurement processes, and policies for acquisition governance have had to keep pace. As Berteau, Ben-Ari, and Zlatnik (2009) noted in a report by CSIS, “Current approaches [to acquisition] were developed years ago in an environment where the government was technically astute and worked closely with one vertically integrated contractor per program” (p. 2). Today, acquisition programs regularly involve large networks of contractors that integrate increasingly complex technologies into SoS, but the government has not maintained the kind of strong technical workforce necessary for it to stay on top of these emerging technologies. This gap makes it more difficult for requirement setters to independently forecast development schedules and component compatibility.

By examining the applications of weapon system acquisition models over time, this analysis provides a basis for the CSIS acquisition governance framework in this report and the application of that framework to the case studies presented as follows. The analysis outlines two areas of foundational knowledge. First, how have preferred models for acquisition governance evolved over time? Second, how does growing complexity challenge the contemporary models for acquisition governance?

Evolution of Acquisition Governance Models—Historical Context

The DoD has exercised different approaches to acquisition over time, favoring various divisions of responsibility between industry suppliers and government customers. Harvey Sapolsky (2009) outlined these models in a paper published by CSIS, titled *Models for Governing Large Systems Projects*. Sapolsky’s discussion suggests that the government has preferred to push more of the functional responsibilities of acquisition away from itself and toward industry contractors over time. This is in part a product of the flow of human capital toward the private sector and the erosion of the government’s internal engineering expertise relative to industry. While the elements of the Sapolsky (2009) model have different levels of analytic validation, the overall trends of skill and task migration from government to industry are well-documented and difficult to dispute.

The original model for weapons acquisition dates back to the earliest days of the U.S. defense infrastructure. At that time, the U.S. Navy could specify the warship it needed along with the design, construction, and outfitting of the ship. The Navy managed and performed production operations and generated technical requirements at all levels of the acquisition chain. Sapolsky (2009) titled this acquisition approach the “Arsenal Model,” under which the government forms its own industrial base. It relies on scientists and engineers within the federal government’s defense workforce. It is still employed to an extent today through the DoD’s network of arsenals and maintenance depots around the country.

An acquisition approach known as the “Contract Model” involves greater industry participation in technical execution than the Arsenal Model. This model became dominant with the beginning of the Cold War. Increasingly, the government relied on the expertise and responsiveness of contractors to meet its needs for larger and more technically demanding weapon systems. Over time, the government maintained a workforce in contracting and acquisition program governance but began to outsource more technical execution to industry.

As weapons became more complex and management of these systems needed improvement, the acquisition community developed a preference for greater industry involvement under the Weapon System Manager Model of acquisition. This model employs large contractors responsible for the administration and coordination of a network of contractors working on subtasks integral to the overall acquisition effort. Passing responsibility to the weapon system managers has the advantage of involving large and responsive contractors that assist the integration of more complex systems that originate from a larger network of stakeholders.

As the DoD began to manage less of the implementation and program management capabilities, it also started to lose its ability to provide technical direction for its acquisition efforts. This was accelerated by the end of the Cold War, when technical direction almost exclusively became the purview of industry. At this time, DoD leadership preserved combat capabilities while seeking savings within the technical functions of the services. This fourth model, known as the Outsourcing Model, grew more prevalent due to greater preference for private-sector program implementation over government implementation.

The flow of more tasks and responsibility toward industry contributed to the growth of what Sapolsky (2009) called the "Lead System Integrator (LSI) Model" more commonly used today. Because the LSI Model has been adopted to describe a specific type of contracting, this paper refers to Sapolsky's LSI Model as the "System Integration (SI) Model." In the SI Model, capabilities requirements are still controlled by military officers, but technical expertise is contracted to SIs to advance the capabilities of the planned weapon systems.

As the adaptation of Sapolsky's (2009) governance models in Table 1 indicates, the evolution of acquisition governance models over time—from preference toward the Arsenal Model in the earliest days of U.S. defense acquisition to greater use of the SI Model in large weapon systems acquisition today—is characterized by the gradual removal of responsibility from the government buyer. In theory, moving all of the functions formerly performed by the government to industry contractors lessens the personnel burden associated with the maintenance of a large in-house acquisition workforce. Furthermore, reliance upon industry to designate technologies that meet warfighter demands should allow government buyers to internalize Moore's Law and procure and deploy advanced capabilities in a shorter amount of time. However, this evolution has fallen short of expectations in practice and may instead be contributing to cost and schedule overruns and compromising the government's ability to manage large-scale acquisition efforts.

Table 1. **Evolution of Acquisition Governance Models**
(Sapolsky, 2009)

Model ⇨ / Task ⇩	ARSENAL	CONTRACT	WEAPON SYSTEM MANAGER	OUTSOURCING TO PRIVATE ARSENAL	SYSTEM INTEGRATOR
PROGRAM REQUIREMENTS	Government	Government	Government	Government	Government/ Industry
TECHNICAL DIRECTION	Government	Government	Government	Industry	Industry
PROGRAM MANAGEMENT	Government	Government	Industry	Industry	Industry
TECHNICAL EXECUTION	Government	Industry	Industry	Industry	Industry
EXTERNAL ENVIRONMENT	Infrequent wars Little commercial application of military tech	Some commercial application of military tech Private sector pays better, can be more responsive	Weapons become more complicated /complex Coordination of sub-systems becomes important Large companies can leverage political support more effectively	Government begins to lose in-house tech capabilities Outsourcing becomes increasingly acceptable	Loss of in-house government tech capabilities leads to inability to define what's possible

Note. The table has been adapted by CSIS and also appears in G. Ben-Ari and P. Chao's *Organizing for a Complex World: Developing Tomorrow's Defense and Net-Centric Systems* (p. 26).

The changing distribution of responsibilities between the industry supplier and the government customer, reflected in the Sapolsky (2009) model, serves to frame acquisition governance challenges in SoS acquisition. In addition, there are two distinct models for the direction of acquisition governance. In the traditional approach to acquisition governance, the capabilities comprising a SoS are governed downward from the program level. In an enterprise-wide governance approach, governance flows upward from the capabilities level. Because the "enterprise approach" is an emerging model that is currently evolving to meet the demands of SoS complexity, its application is not evident in early-stage acquisition governance models. Instead, traditional, top-down approaches to acquisition governance have been most prevalent throughout the evolution of governance models, from the Arsenal Model at the dawn of U.S. armed services to the SI Model today.

Complexity—The Problem Defined

The DoD's preferences for acquisition governance models have changed over time, reflecting the flow of human capital, technical knowledge, and production assets away from the government. In the process, the growth in weapon system complexity has outgrown existing models. Warfighters are increasingly reliant on capabilities developed as part of a broader SoS capability. These complex SoS are noteworthy for their size, scope, and inherent complexity. In this context, *complexity* is used to mean that systems consist of multiple elements that are typically developed and managed by more than one organization. This management dispersion adds to the complexity of unpredictable interactions inherent in

complex SoS. Furthermore, these system elements are often part of more than one set of capabilities; that is, a given system may be part of several SoS. This poses significant management and governance challenges. However, the payoff of successful delivery is the ability to achieve capabilities far greater than those delivered through individual programs or systems.

The divergence of current governance models from the service's complex SoS capabilities requirements is apparent in the pervasive acquisition challenges that the DoD faces. As capabilities become more complex, they demand a DoD systems engineering workforce that may exceed what the government customer can offer. Additionally, the DoD faces operational requirements from the demand for systems operability in multiple roles, missions, and environments. These challenges can result in structural difficulties for SoS capabilities that may not exist in traditional acquisition approaches. For instance, knowledge sharing—a straightforward task in traditional acquisition—faces new challenges in complex SoS acquisition efforts. Knowledge ownership and incentives for sharing become less clear, adding to the host of governance process shortfalls. Compounding these challenges in technology, operational requirements, and structure, the DoD organizations needed to develop and deploy the SoS capabilities are bigger and more difficult to manage and maintain than traditional acquisition organizations, particularly under the SI Model.

The growing divide between acquisition governance models and acquisition in practice is also clear in SoS acquisition outcomes. The government customers' ability to deliver complex SoS capabilities on cost in particular is declining. According to the Government Accountability Office (GAO; 2013), more than 86 Major Defense Acquisition Programs (MDAPs) in fiscal year 2012 showed approximately $400 billion in aggregated cost overruns since their first full-year estimates, representing a 4% ($90 billion) growth in development costs and a 5% ($290 billion) growth in costs of procurement. As dramatic as this cost growth is, this latest annual report from the GAO is actually anomalous when compared against even greater cost growth in the 2012 GAO report. In that iteration, 96 MDAPs existing in that year had grown an aggregated $447 billion in excess of their original estimated costs (GAO, 2012). Given the expected impact of sequestration, the 2012 GAO report is likely to more accurately represent the trend in cost growth. That trend is particularly evident when compared with the 2007 GAO report, which cited 64 MDAPs in the DoD's accounts that had grown at an average annual rate of 4.9%. This produced a total annual cost growth of $165 billion by those programs in that year (GAO, 2007, p. 8). This indicates that cost overruns grew 170.9% in the years between 2006 and 2011.

The government is also encountering challenges in keeping its major weapons programs on schedule. In its latest report, the GAO (2013) found that MDAPs experienced an average delay of 27 months in reaching initial operational capability. This figure exceeds the 2012 estimate of 23 months in average delay (GAO, 2012, pp. 6–7). Combined with the upward trend in cost growth over time, this track record indicates that existing governance and management tools no longer suffice for today's complex weapon systems.

As cost and schedule overrun trends illustrate, delivering SoS depends on getting governance right. However, the traditional service-centric approach to acquisition governance is not sufficiently flexible to meet the needs of SoS. Specifically, flexibility is limited in two ways.

First, the current process of generating requirements does not allow for the integration of changes in user needs. Because complex SoSs are inherently dynamic, non-linear, and risk-intensive, acquisition leadership's ability to react to changes in user needs is critical to the successful delivery of SoS capabilities. Structured but flexible oversight

procedures improve alignment between DoD requirements and fielded systems by establishing clear systems-level metrics and measuring progress toward declared goals. Systems must also be able to respond to changes in external factors in order to ensure that the SoS capability is as relevant when it reaches the production and deployment phase as it was in pre-acquisition phases. These factors could include macro-level changes in the security environment and technological advances as well as micro-level changes in organizational politics and acquisition effort leadership.

Second, successful acquisition delivery requires the "power of the purse" to direct solutions and approaches. In order to direct efforts toward certain capabilities, program leadership must be able to dedicate resources such as real contracting dollars, as well as human capital and allocations for other overhead costs, to certain system efforts. However, budgetary power is limited when individual services and defense agencies are the highest level of governance, due to the relatively more limited ability of those stakeholders to guarantee funds for the system or to be able to shift and reapportion them at the system level. The process by which funds are secured also limits flexibility; the DoD's 20-month-plus budget cycle that precedes actual appropriation may lead the DoD to acquire technologies that are bleeding-edge when a budget is begun but that may become outdated by the time the budget is enacted.

Given the limited effectiveness of traditional service-centric governance approaches, it is useful to look at new, enterprise-wide governance models for the acquisition and delivery of complex SoS capabilities. Numerous platforms and systems comprise SoS, and the interactions of these components are highly unpredictable. Coordination of these internal constituent systems is necessary to achieve the desired SoS capability, which otherwise would be out of reach for any single component alone. An enterprise-wide approach to governance would facilitate oversight and accountability of the systems' individual components to achieve that coordination. The following case study was selected to reflect both the traditional and enterprise approaches.

Acquisition Governance Case Studies

CSIS is analyzing selected SoS case studies in order to understand the merits and demerits of existing governance models for SoS acquisition. Once complete, and adding to the following two case studies, the case studies will contribute to a theoretical framework for the development of a new acquisition governance model.

To date, the CSIS project team has conducted preliminary analysis of seven SoS case studies. Two relevant case studies are included in this interim report. The remaining case studies will be added to the final report. The FCS program case presents an example of a so-called traditional governance approach, in which governance of all systems is centralized at the program level and a program of record is established by the customer to procure the end-user capability. The MDA effort provides an example of an enterprise-wide approach to governance, in which families of capabilities are procured under the umbrella of larger programs with the MDA end-user capability in mind. Together, the two cases permit the introduction of a CSIS framework for the identification and application of acquisition governance attributes. Next, this interim report discusses the FCS and MDA case studies to offer a high-level picture of program performance. Finally, the framework is used to compare the FCS and MDA governance attributes and observe their relationship to program performance.

Applying the CSIS Acquisition Governance Framework in Case Study Analysis

Through previous work on acquisition models for the Office of the Secretary of Defense (OSD), CSIS has developed a framework for analyzing acquisition program

governance. The framework of eight attributes is presented for public release for the first time in Figure 1.

This framework is based on the CSIS process of research on SoS governance models, interviews with programmatic stakeholders and industry leaders, and findings revision through input from SoS experts. The framework attributes represent concerns, questions, and issues that must be addressed for an organization to be able to deliver SoS capabilities effectively. The significance of these attributes varies depending on the SoS being analyzed, but all eight attributes add important value to the final analysis.

GOVERNANCE ATTRIBUTE	DESCRIPTION
LEVEL OF ORGANIZATIONAL FOCUS	The level at which SoS governance occurs within the organization. This is not the same as systems/capabilities focus or technical focus, both of which are outside the scope of the CSIS SoS governance analysis.
INTEGRATION OF FUNCTIONAL END-USER NEEDS	The mechanism(s) and frequency with which the functional needs of end-users are built into the system-of-systems, and at which points in the process of delivering the system-of-systems this incorporation occurs.
DECISION-MAKING AUTHORITY	The formal mechanism by which delivery of systems-of-systems is governed, including how budget is allocated, standards are set, tradeoffs are managed, and inconsistencies are adjudicated.
ENFORCEMENT	The mechanisms and level of management oversight by which the objectives of the SoS capability to be delivered are ensured, including measurements and program metrics.
WORKFORCE	The examination of SoS workforce structures, unity of mission, and capability development and enhancement through use of contracted support.
INCENTIVE STRUCTURE	The alignment between enterprise goals and the incentive and reward structures of the components that implement them.
KNOWLEDGE OWNERSHIP / ACCESS TO KNOWLEDGE	The accessibility of information regarding the operating environment, technical standards, and other elements that comprise the system-of-systems.
RISK ASSESSMENT / RISK MANAGEMENT	Risk assessments and management strategies tailored to mission accomplishment and the flexibility and resilience required for delivering systems-of-systems in the face of unforeseen developments.

Figure 1. Eight Attributes of Acquisition Governance

This framework enables side-by-side comparison of programs like FCS and MDA. As demonstrated in the following case study comparison, the comprehensive acquisition governance framework allows dissection of an acquisition effort in order to examine the eight governance attributes independent of one another and to determine how the attributes correlate with quantitative performance metrics (e.g., gaps between test results and planned goals, schedule delays in months, cost overruns in billions of dollars, etc.). As part of this analysis, CSIS will be able to identify which attributes correspond more closely with poor acquisition governance. The analysis will also clarify and improve the eight-attribute framework outlining best practices in SoS acquisition governance.

Figure 2 compares the FCS and MDA cases to illustrate how this methodology can be applied in practice. The comparison offers a notional qualitative analysis of program characteristics for each of the eight attributes. Program characteristics are presented without

direct comparison to one another and independent of the outcomes and performance of the programs themselves. Instead, this first-level comparison serves to compose an initial profile of the programs for further analysis of best practices.

Future Combat Systems Case Study

The FCS program is one example of how traditional acquisition governance has fallen short of meeting the challenges of complexity. This program, officially initiated with a four-team competition in February 2000 and terminated nine years later in 2009, was to be the Army's major research, development, and acquisition program. It initially consisted of 18 manned and unmanned systems linked together via a network. As the largest acquisition program ever attempted by the Army, FCS was envisioned to transform the service by replacing current systems such as the M-1 Abrams tank and the M-2 Bradley infantry fighting vehicle as well as by adding new capabilities. The advanced technologies associated with the FCS program, in addition to the challenge of integrating subsystems, posed large problems for successful development and contributed to the program's high level of risk. The total cost for FCS ballooned to an estimated $200 billion at the time of its cancellation (Corrin, 2012).

In May 2000, the Defense Advanced Research Projects Agency (DARPA) awarded four contracts to four industry teams to develop FCS designs. The Army awarded the LSI contract to a team led by Boeing and Science Applications International Corporation (SAIC) in March 2002 after nearly two years of design evaluation. The Boeing and SAIC team worked with more than 550 contractors and subcontractors in 41 states.

The termination of FCS can be attributed to any of a number of problems. Three related to program flexibility are worth discussing here. First, the capabilities being developed under the program had fallen out of alignment with warfighter needs. The Army began developing the FCS concept in the 1990s, and the service had designed the system to meet requirements for rapid deployability, in-theater tactical maneuverability, and survivability. These requirements were not suited to the close-combat and urban terrain operations in which the Army was engaged post-9/11 (Pernin et al., 2012, pp. 54–57). Second, several evolutionary capabilities essential to program success were not developed at the projected pace. In its attempt to avoid capabilities obsolescence, the Army chose evolutionary capabilities to meet the core survivability requirements of the manned ground vehicle (MGV). The situational awareness and understanding (SA/SU) network, for example, was consistently behind its projected development schedule (Pernin et al., 2012, pp. 109–110, 264). Third, in part due to the slow pace of capabilities development and the high rate of expenditure, remaining resources were low compared with the level of progress achieved. Sources projected in 2009 that 60% of the project's funding would be exhausted by the Preliminary Design Review, leaving the remainder to cover the entire system development phase (GAO, 2012). In the end, FCS was terminated, and the Army continued the development of some select families of capabilities as individual systems (Malenic, 2009, 2010).

Maritime Domain Awareness Case Study

MDA provides a useful contrast with traditional acquisition governance. MDA is not a formal program like FCS and other traditional acquisition efforts. Instead, this enterprise approach to capabilities acquisition is an interagency, international strategy to deal with threats and challenges in maritime theaters. The MDA system aims to support and integrate government-wide efforts to collect, fuse, analyze, and disseminate data among defense, law enforcement, and border protection officials from the U.S. and allied countries, creating a cross-domain common operating view.

The MDA concept originated from a 1998 presidential initiative and was developed further in two presidential directives (NSPD-41 and HSPD-13) released on December 21, 2004. Since then, the established technology investment strategy and its supporting offices and business systems have undergone numerous changes. Currently, the National Maritime Intelligence-Integration Office (NMIO), under the direction of appointees from the Navy and Coast Guard, is the nominal lead for MDA's information exchange portal, the open architecture tool at the heart of the MDA mission.

Two stages or "spirals" of technology acquisition were planned to develop and integrate the infrastructure that MDA would need to achieve its mission objectives. While a number of policy directives have offered strategic direction, the participating agencies—primarily the U.S. Coast Guard and Navy, with some additional contributions from Customs and Border Protection—have mostly led their own initiatives. Each entity is free to develop its own definition of maritime domain awareness. These definitions may not fit together across the enterprise, even though they are generated from the bottom up. As one former MDA executive expressed in a conversation with CSIS, "To some, binoculars are a maritime domain awareness technology."

Analysis of budget requests from 2009 to the present day shows that to date, services have procured MDA assets mostly under the umbrella of larger program elements. Furthermore, with the exception of some research and development programs led by the Office of Naval Research (ONR), the services have procured primarily non-development items (NDI) and commercial off-the shelf (COTS) products. As a result of this approach to acquisition, investments in MDA are difficult to quantify, progress is difficult to monitor, and oversight is difficult to ensure.

Individually, the attributes described in Figure 2 underscore some merits and demerits of both traditional and enterprise-wide approaches to acquisition governance. The attributes also offer additional insight into acquisition governance best practices when viewed in comparison across the two case study programs. Thus, there are key attribute-specific takeaways offered by the case studies, both in isolation and compared to one another. These takeaways are discussed in Figure 2.

GOVERNANCE ATTRIBUTE	FUTURE COMBAT SYSTEMS	MARITIME DOMAIN AWARENESS
LEVEL OF ORGANIZATIONAL FOCUS	• Focus on the final product, governance centralized at the program level	• Implementation at sub-program level • Enterprise-level integration has been prescribed but not implemented
INTEGRATION OF FUNCTIONAL END-USER NEEDS	• Top-down requirements-setting produced low integration of end-user needs into ongoing FCS development	• MDA infrastructure integrates end-user needs as they were described at program start • Sub-program funding allows for folding of new needs into spirals of technologies
DECISION-MAKING AUTHORITY	• Governance model was organized to segregate decision-making and push it downward	• Program executives choose whether and to what extent MDA should be incorporated in investment objectives
ENFORCEMENT	• Other Transaction Authority contract format with minimal management oversight of contractors	• No substantial enforcement guiding MDA-relevant programs to desired end state • Lacks funding and structure necessary for cross-service enforcement of MDA goals
WORKFORCE	• Contractor program managers act in the role of acquisition leadership • IPTs co-led by one appointee from the LSI and one appointee from the Army	• No investments in new workforce development, relying instead on existing acquisition workforce at individual program offices
INCENTIVE STRUCTURE	• Performance incentives based on completion of program events (e.g. design reviews); Cost incentives based on projected life-cycle cost	• Program managers have no incentive to incorporate MDA objectives into requirements generation or procurement planning
KNOWLEDGE OWNERSHIP / ACCESS TO KNOWLEDGE	• Significant stovepiping of knowledge; Sub-contractors hesitant to submit competitive information to LSI team	• Informal knowledge sharing occurs through white papers and other forms of thought-leadership
RISK ASSESSMENT / RISK MANAGEMENT	• PM FCS and the LSI conducted independent assessments of program health periodically using an Earned Value Management System (EVMS)	• Lack of meaningful leadership mechanisms with no identified tools for management of unforeseen circumstances

Figure 2. Comparison of FCS and MDA Acquisition Governance Attributes

The cases illustrate that the impact of the level of organizational focus in acquisition governance is dependent on how much oversight is in place. In FCS, the concentration of organizational focus at the program level resulted in slow responsiveness to changing warfighter needs and factional protection of capabilities families, such as manned ground vehicles. Rigid oversight from the top constrained the program’s progress.

In contrast with this organizational rigidity, the MDA case demonstrates that a more liberal organizational focus in an enterprise-wide governance approach also presents challenges. MDA capabilities acquisition efforts are divided among numerous programs, and the responsibilities for acquisition governance decisions are siloed within separate and occasionally unrelated programs. Progress on the MDA mission has been slow in part because of this dynamic. With greater oversight on the direction of capabilities development, it is possible that MDA assets could reach the theater more quickly and interact more easily.

Additionally, the case comparison suggests that setting requirements and adjusting them to the changing demands of the end user is difficult under top-down governance, whether the responsibility of governance falls to the government or industry. As discussed previously, industry began taking the requirements generation role from the government during the evolution of acquisition governance from the Weapon System Manager Model to the Arsenal Model. The reason for this natural progression was that the government no longer had the technical astuteness to manage more advanced technical requirements. However, the FCS industry LSI also failed to adjust requirements properly and was similarly hamstrung in its efforts to manage subsystem capabilities. Indeed, the size of the

subcontractor network and the diversity of the systems and capabilities being acquired exposed the insufficiencies of a traditional approach to governance.

The MDA effort, by comparison, has demonstrated more agility in its ability to adjust requirements to the end-user community's changing demands. By distributing responsibilities for generating requirements across a network of programs and subprograms, the MDA effort has enabled those closest to the end user to determine capabilities requirements. While guidance from the DoD Executive Agent for Maritime Awareness has provided a framework for the capabilities required in its spirals of technology, the participating offices are free to determine what specific systems fit into that framework. The flaw in this approach is that the definition of maritime domain awareness per se can differ among the offices. Furthermore, there are no mechanisms to ensure that tasks are delegated between government and industry stakeholders in a way that enables timely and cost-efficient delivery of systems and subsystems. A critical system could be delayed due to a unit-level acquisition effort being governed under the LSI Model, for example, with potentially damaging consequences for the broader SoS.

Thus, these differences in the two attributes for Level of Organizational Focus and Integration of Functional End-User Needs help to identify challenges in both the traditional and enterprise-wide approaches to acquisition governance. In contrast, similarities between FCS and MDA illustrate that some governance attributes transcend the dimension of task delegation between the government and industry stakeholder communities. Specifically, a comparison of the attributes for Enforcement, Incentive Structure, and Knowledge Ownership shows that there are critical oversight functions that both industry and government need to get right in order to facilitate complex SoS acquisition.

The FCS and MDA cases both illustrate that system delivery suffers when proper oversight enforcement mechanisms are not in place. Use of an Other Transaction Authority (OTA) contract in FCS created oversight challenges at the systems level, resulting in limited enforcement of cost and technical readiness standards. It is also reported that the LSI issued contracts with standards below those in its contract with the Army. The Army addressed these issues when it revised the contract to a Federal Acquisition Regulation (FAR) contract and established processes for greater Army involvement in capabilities selection and requirements.

Enforcement has been lacking at both the systems and SoS level within MDA. Because the MDA effort is a loose network of individual program offices guided by overarching objectives without prescriptive benchmarks, the DoD has encountered a good deal of difficulty in moving it forward and gauging its progress.

Effective incentives for capability delivery on schedule and on cost were also noticeably absent in both programs. In the case of FCS, performance incentives were based on the completion of program events such as design reviews, rather than on a meaningful metrics-based assessment of technical performance. The misalignment of technical requirements between the LSI team and the government compounded this problem, detracting from the effectiveness of incentives in encouraging on-schedule capability delivery. Cost incentives also were based on artificial benchmarks, assessing contractor cost-performance based on the projected life cycle cost of capabilities rather than on their actual cost track record.

The patchwork of incentives in MDA also appears to be ineffective. In contrast with the artificial incentives in FCS, MDA has few incentives at all on the SoS level. On the systems level, individual programs are responsible for the establishment of incentives for the

delivery of individual capabilities. A more explicit incentives infrastructure may be necessary to encourage greater commitment to the MDA objectives.

Finally, the FCS and MDA cases underscore the importance of knowledge ownership in delivering SoS capabilities. Significant stovepiping was apparent in the FCS case, where the use of an industry-led acquisition workforce raised concerns among subcontractors about the fairness of competition and the use of proprietary information. These concerns created barriers to transparent information sharing across and within programs. While stovepiping has not been prevalent in MDA, unstructured information-sharing processes, combined with a lack of uniform maritime domain awareness definitions, have hampered knowledge sharing among the MDA stakeholders.

Toward a New Acquisition Governance Model

The case study analysis presented previously offers several preliminary key findings for the CSIS effort to identify governance best practices in SoS acquisition. The cases begin to support three themes in the creation of a new governance model.

First, SoS acquisition governance benefits from having strong and structured management oversight procedures tied to documented results. Shared FCS and MDA shortcomings in Enforcement and Incentive Structure originated in insufficient or otherwise flawed oversight. The reported inadequacies of government oversight over the LSI exacerbated technical and programmatic flaws in FCS. In MDA, minimal oversight over a broad network of government customers has caused problems with both the establishment of requirements and the measurement of progress.

Second, existing approaches to acquisition are challenged by high barriers to knowledge sharing and a lack of clarity regarding the ownership of this knowledge. The use of an LSI contractor in FCS created disincentives to information sharing, both within the program and with the customer. Industry stakeholders perceived that information sharing between and among their peers would damage their competitiveness and compromise their proprietary information. While these structural impediments to knowledge sharing are not apparent in MDA, that program instead has minimal incentives to promote knowledge sharing. In other words, explicit barriers do not exist between and among MDA stakeholders, but there is insufficient payoff for knowledge sharing outside of lower level systems.

Third, a new model of acquisition governance may require more task sharing between government and industry than has been seen in prior models. Some problems with FCS are attributable to that program's use of an SI Model of acquisition governance. However, similar problems apparent in the MDA program show that designating other tasks to government—in the case of that program, the task of Program Management—is not sufficient to fix problems of management oversight. In fact, a comparison of MDA and FCS shows that replacing industry with government in non-Program Requirements tasks of the SI Model to create a new model seems to have created additional problems with the lead agency's ability to coordinate and enforce progress among other participating agencies.

Conclusion

As government demands to defeat threats to global security cause systems of capabilities to grow in size and complexity, the limited effectiveness of existing models of acquisition governance is becoming more apparent. The initial analysis reflected in this interim report underscores the importance of further research on best practices in acquisition governance with a view toward the creation of a new model. The example case studies presented here are a first step in an effort by CSIS to identify those best practices.

The case studies illustrate that getting governance right would involve a thorough analysis of how program outcomes are affected by a comprehensive set of governance attributes. Each of the eight attributes used here represents a different but vital element of any acquisition effort. Moving forward, the CSIS Complexity project team will perform an analysis similar to the one discussed previously across a total of seven SoS acquisition case studies to identify what practices in acquisition governance contribute to program success and what practices make successful capabilities development and acquisition more difficult to achieve. The preliminary cases presented here will also be refined based on the results of an ongoing primary research effort.

This interim report serves as a progress report on efforts by CSIS to identify best practices in SoS acquisition governance. This effort will incorporate additional case studies in the coming months and will conclude in September 2013 with a full report on best practices and a framework for new governance models. The report will be presented at the May 2014 Naval Postgraduate School Acquisition Research Symposium.

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Acknowledgement

This paper is dedicated to the memory of Guy Ben-Ari (1973–2013). Throughout his career, Guy contributed pioneering thought to the field of innovation in the defense industry. He will be missed.

The Making of a DoD Acquisition Lead System Integrator (LSI)

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Abstract

The complexity of developing and acquiring weapons systems continues to increase due to highly integrated system architectures, rapid technology evolution, and emergence of highly diverse set of missions. The imperatives of system-of-systems (SoS) integration and interoperability (I&I) further complicate the system acquisition process. These challenges continue to frustrate completing the acquisition of systems within time and budget goals.

The DoD has commonly assigned the role of the lead system integrator (LSI) to a prime contractor. This is fraught with many issues related to conflict of interest, performance, and defining clear roles and responsibilities (especially the inherent role of government). The DoD has indicated that, in some cases, the LSI responsibilities should migrate back to the DoD.

In this paper, we discuss the roles of the LSI, where DoD acquisition skills may need to be strengthened to perform as the LSI, and discuss methods and tools to do so. This paper is a result of multi-year discussions and research with a major Naval Systems Command to find a path to faster time-to-market and higher levels of interoperability and integration of our weapons system acquisitions.

Introduction

What is a lead system integrator (LSI)? Although a broader concept than its simple acronym, commonly, the role of the LSI has been turned over to industry in the form of a prime contractor, or team of contractors, hired by the federal government to execute a large, complex, system-of-systems (SoS), defense-related acquisition programs (Grasso, 2007). The need for an LSI is often associated with the acquisition of an SoS or a constituent system to an SoS. SoS programs acquire a collection of various platforms (e.g., ground vehicles, aircraft, and ships) that are to be linked together so as to create a larger, integrated overall system (Lane, 2006).

LSIs are further categorized based on their system development capabilities and responsibilities. Section 805 of the National Defense Authorization Act of Fiscal Year 2006 (2005) defines these two types of LSIs as

1. "Lead system integrators with system responsibility" prime contractors who develop major systems that are not expected at the time of the contract award, as determined by the Secretary of Defense, to perform a substantial portion of the work on the system and major subsystems.
2. "Lead system integrators without system responsibility"—contractors who perform acquisition functions that are closely associated with inherently governmental functions in the development of a major system. LSIs, regardless of type, are subject to the same rules as other federal contractors.

In recent years, the LSI responsibility has been awarded to industry for major DoD acquisitions. However, this has led to conflict-of-interest complications resulting in revised law stating, "No entity performing lead systems integrator functions in the acquisition of a major system by DoD may have any direct financial interest in the development or construction of any individual system or element of any system of systems" (Defense Authorization Act for Fiscal Year 2006, Section 807). As a result, several of the major contractors have divested into companies focused separately on systems integration and product development. An example is Lockheed Martin, where "Lockheed Martin's decision to divest the business was based on the U.S. Government's increased concerns regarding perceived conflicts of interest" (The SI Organization, 2010).

Due to recent failures in some major DoD acquisition programs (examples in GAO, 2007), the DoD has made the decision to use an LSI endure more scrutiny by, in some cases, requiring certification by the Committees on Armed Services for both the Senate and the House (OSD, 2007). This has led some to conclude that to reduce complexities and risks associated with the use of contractors as the LSIs, the DoD should consider (Grasso, 2007):

- prohibiting the use of private-sector LSIs in future acquisition programs;
- reducing the possible need for private-sector LSIs by building the defense civilian and military acquisition workforces back up, and having the DoD assume the role of the LSI, and requiring that DoD manage all SOS programs; and
- implementing the recommendations of the Gansler Commission on improving the acquisition workforce (U.S. Army, 2007).

The following discussion begins with the premise that the DoD concurs with the recommendations above and desires to bring more LSI responsibilities "in house," in particular, engineering responsibilities. Some of the major systems commands are exploring

such a transformation to bring systems to the DoD more quickly while attaining higher levels of interoperability (Young, 2010). If the DoD acquisition community wants to make such a transformation to retain more inherently governmental responsibilities for major system acquisitions, what needs to be done to fortify the systems engineering (SE) workforce skills, SE methods, and SE tools to enable taking on the larger role of the LSI? We use Figure 1 as a context diagram throughout (blue is our focus).

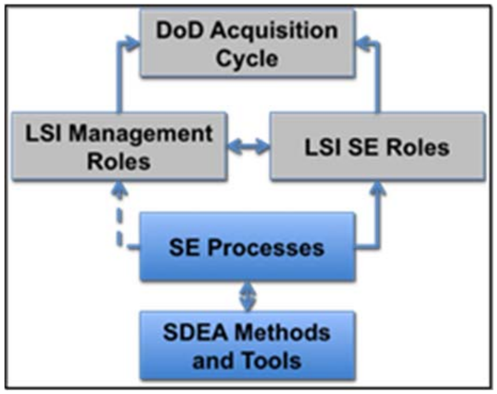

Figure 1. LSI Systems Engineering and Management Roles Are Supported by Systems Engineering Processes, Methods, and Tools

In our previous research (Montgomery, Carlson, & Quartuccio, 2012), we focused on how SE tools could be applied to DoD acquisition SE methods. We introduced a model-base, SE-inspired approach named System Definition-Enabled Acquisition (SDEA) in that research and discussed how SDEA could be instrumental for LSI SE success. What follows extends that previous SE tools perspective to the role of the LSI SE as a result of ongoing research with Naval Air Systems Command (NAVAIR).

Problem Definition and Research Questions

The Defense Authorization Act for Fiscal Year 2006 (Section 807) provides emphasis on the importance that the lead systems engineer on a DoD acquisition be an experienced government employee. Additionally, the DoD ASD(R&E) chief systems engineer, Stephen Welby (2012) summarized the imperatives for DoD SE as follows:

> As the complexity of our systems has increased, so has the need for effective systems engineering throughout the life cycle. We face challenges in implementing robust systems engineering processes, from requirements identification and analysis through technology and architecture selection and assessment, analysis and coordination of complex system design, development, and execution …. We are now increasingly focused on addressing early-acquisition phases including requirements definition, development planning, and early acquisition systems engineering support.

Finally, as stated in a report sponsored by Welby (Systems Engineer Research Center [SERC], 2010), “existing systems engineering tools, processes, and technologies poorly support rapid design changes or capability enhancements within acceptable cost and schedule constraints.”

Problem Statement

The background and guidance presented in the previous section leads to our investigation, focused by the following problem statement: The DoD does not have

adequate SE methods, processes, workflows, and/or tools that support the expansive role of the LSI in major weapons systems acquisitions.

Research Questions

The associated research questions that we have been investigating in order to resolve our problem statement include the following:

- What are key DoD acquisition challenges for the LSI?
- What are the key LSI roles and attributes?
- What is the current state of DoD LSI maturity?
- What SE methods are prime candidates to improve upon to support LSI?
- How can MBSE/SDEA be applied to the LSI?

LSI Challenges

Regardless of the government/contractor ownership of LSI SE responsibilities, the challenges to current acquisitions are diverse, not necessarily new, and are discussed as follows (derived from Montgomery et al., 2012).

Complex System Acquisition

The current DoD acquisition process (see Figure 2), as specified in DoD 5000, WSARA, and a long heritage of acquisition experience, is based on the acquisition of stand-alone systems. Today's system acquisitions are more co-dependent on the development of other complex systems in an SoS environment. This requires a higher level of coupling between system engineering and the acquisition process to support SoS, as well as the need for higher levels of LSI support.

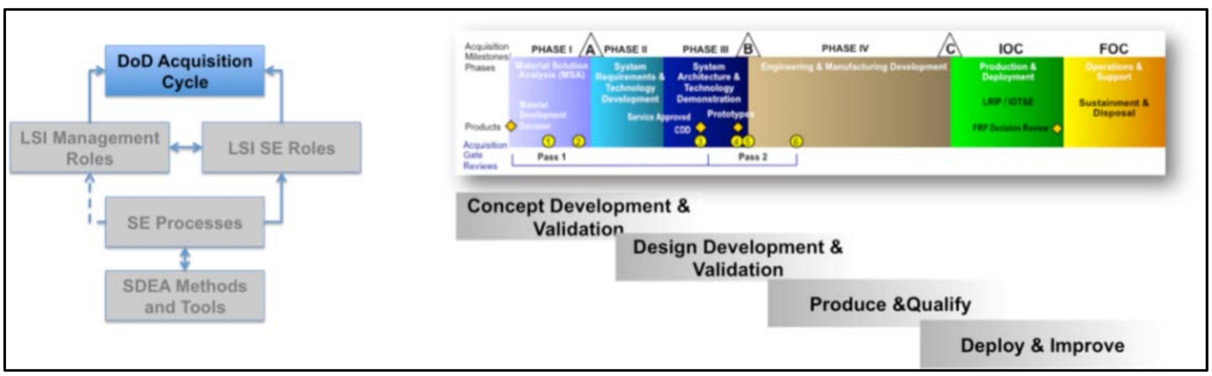

Figure 2. DoD 5000 Acquisition Process

A problem that continues to frustrate this acquisition timeline and increase program costs is both system complexity and SoS interoperability. Many acquisitions are the integration of several systems that are being acquired and developed independently and for their own purposes. This SoS method presents a new and interesting level of complexity for system engineers because system engineers rarely have the opportunity to affect the design of these co-dependent systems. The functionality, interfaces, operational objectives, and intended system environments all provide a challenge to ensuring that the SoS can be integrated successfully while producing new emergent behaviors that are predictable and satisfy the user needs. Couple all of this complexity and SoS realities to the existing system engineering methods, practices, principles, organization behaviors, and workforce skills, and the need for SDEA methods and tools becomes clearer to resolve many of the following challenges.

Acquisition Timeliness

Acquisitions are too slow-to-market. Acquisition schedules are often document-driven and technical review-driven processes and non-adaptive to changing or emergent requirements. DoD 5000 emphasizes prototypes early in acquisition, requiring a tightly coupled engineering system to meet engineering goals, objectives, and requirements. The LSI SE needs to be diligent to ensure pre-planned programmed improvements (P3Is) are enabled and that tools provide enduring design data.

Acquisition Process

The Acquisition process is not LSI design-driven. The DoD 5000 acquisition process is oversight-driven and document-driven and designed such that government engineers provide the oversight while the contractors provide the content. It is likely that DoD 5000 will ultimately have to be revised to define a process more aligned to the government providing LSI SE direction. An example would be to exploit a process that that could be streamlined as a result of the government and user community retaining more LSI SE activities and direct engagement with the development of the baseline in lieu of merely reviewing the progress of the contract.

System Complexity

LSI engineering capabilities do not always support design and acquisition of highly complex systems. Simple systems and complex systems proceed through the acquisition process essentially the same. The role of the LSI, however, is more applicable for the needs of complex systems with a significant emphasis on defining the interaction of systems along with robustness of the system solution. This will require a dramatically different way of defining the LSI engineering process and how it integrates with the program management processes. An example is employment of tools and methods to provide the ability to assess SoS performance and emergent system behaviors in a quantifiable manner. Currently, the ability to predict, manage, and control such emergent behaviors can be elusive.

Integration and Interoperability

Systems often fail at integration or do not interoperate effectively. Successful integration of systems, especially SoS, is challenged by functional gaps and overlaps among the systems' complex interfaces and a large number of internal and external system interfaces. SoS integration also demands the interoperability among these systems, as well as the interoperability outside of the system for other systems that are codependent. The LSI needs SE tools and methods that define and manage risks associated with these critical functions and interfaces.

Total Ownership Costs

Prediction and control of total ownership costs (TOC) is difficult. The acquisition cost incurred during the development cycle is only a fraction of the total ownership cost of any system. The LSI needs to have very detailed, predictable, and repeatable behavior modeling of both the acquired system and external systems in order to accurately predict and control TOC.

Engineering Workforce

The veteran engineers are rapidly retiring and not being replaced with engineers with commensurate experience. The system design process and SE tools need to provide high levels of repeatability and quantifiability that is less dependent on engineering judgment and more dependent on metrics that provide a highly refined engineering solution. Given that many veteran engineers are retiring, there is a need to provide system design-driven

methods to a younger engineering community. A system is needed that also provides project-to-project consistency and repeatability.

Systems Engineering Attributes and Roles of an LSI

LSI Attributes

Not all DoD acquisitions need to be managed by an LSI. Many systems can be acquired with small teams where complexity and risk are relatively easy to manage. The following is a list that includes attributes of program and system designs where the need for an LSI may be more imperative (partially derived from Loudin, 2010):

- Program importance and span of impact—high risk, large cost, or expansive interoperability impacts to the enterprise
- System or SoS complexity—large-scale complexity with a large number of high-consequence risks, external SoS interfaces and interactions, and high likelihood of unanticipated, negative emergent behaviors
- Stakeholder relationships—Collaborative versus command-and-control contractor/government/fleet user interactions are necessary
- Organization agility is required to organize around acquisition (versus the obverse)
- DoD determines that ownership of critical data and/or DoD reuse of critical IP is mandated
- “National teaming” is required to ensure enterprise-level SoS issues are intrinsic to system success
- Acknowledgement and acceptance of higher system design and acquisition risks
- Rapid identification and adaptation of emergent opportunities are essential
- Strong integration leadership and control is required
- Low barriers to entry for technology and innovation need to be established and maintained throughout the life cycle
- Disciplined and rigorous standards demanded for integration of other systems into the enterprise

LSI Roles

The roles of the LSI are similar to the roles of any SE or system integrator (SI). The primary difference is the span of design and integration authority that persists throughout the system acquisition and/or complete life cycle. The following are a sampling of the LSI roles that are more expansive than traditional SE/SI:

- Design: Act as the primary designer (sometime referred to as the “design agent”). Design includes system and SoS designs. Roles include conceptual design, architectural design (operational, functional, physical, interface, qualification), and integration and qualification designs.
- Source selection: Responsible for providing solicitation packages, reviewing and evaluating proposals, and selecting and awarding the contract to component, subsystem, system, or product provider. Component-level solicitation has often been assigned to prime contractors.

- Subcontractor selection: Survey, vetting, and selection of providers of components or services. Component-level selection has often been assigned to prime contractors.
- Supplier chain management: Engagement within the domains of hardware and software configuration item selection, sources of supply, and manufacture.
- Trade-off studies: Conduct of objective trade-off studies and analysis of system challenges, risks, and opportunities.
- System baseline management: Definition, control, and management of system design baselines, configuration management, and realized configurations.
- Rigorous, multi-system definition and management of interfaces, taxonomy, system structures, and so forth.
- Coordinator (and funder) of contributing research.
- End-to-end span of authority and control for baseline control and management of the system design, development, integration, qualification, and deployment.
- Qualification (“V&V”): Ultimate responsibility for developmental (verification), operational (validation), and acceptance qualification success.
- Sustainment/suitability: Responsible for sustainment and suitability design of the system and impact analysis of SoS sustainment strategies.

Current State of the DoD LSI

How do many engineering organizations operate today in DoD acquisition? There have been many strains on DoD manpower reductions over recent years, and the result has been to depend heavily on contractors to do the “heavy lifting” in many engineering domains. Although the government retains many subject-matter experts (SMEs), these highly skilled staff are senior, retiring at a rapid rate, and are stretched thin. The larger and more complex the project, the more likely the government has decided to use a large prime or LSI contractor.

The different roles of engineering involvement are shown in Figure 3, spanning from performing the role of the “buyer” for simple systems to the role of “integrator” when acquiring complex systems. (We put forth these role titles just to provide reference; they are not formally accepted throughout DoD). As can be seen, the engineering tasks (requirements engineering, design, etc.) become more expansive as the role approaches that of the LSI (integrator). The roles close to red (bottom of the list) are associated with complex acquisitions. Our assumption is that the government has been performing in the yellow band of this chart during recent years. As previously stated, contractors have been more likely to be assigned the majority of engineering duties as the systems became more complex.

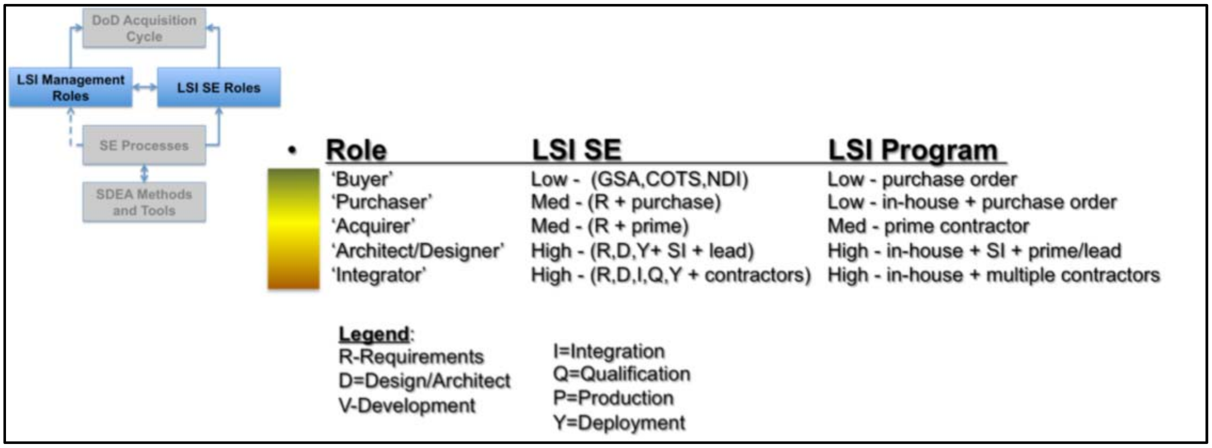

Figure 3. The Engineering Involvement of the DoD Acquirer Becomes More Expansive for Complex ("Integrator" Role) Systems as Compared to Simple ("Buyer" Role) Systems

Figure 4 depicts "traditional" versus "LSI" contractor/government engineering span of authority across the DoD acquisition cycle. The top portion (a) is a typical acquisition cycle that spans from system concept to deployment. The middle portion (b) indicates that the traditional government levels of engineering effort are maximum at the early and latter stages of the acquisition, with the contractor design, production, and integration in the middle. The lower portion (c) of the diagram posits that, if the government is the LSI, the government performs more of the design and integration activities, and the contractor shifts to a more "manufacturing" role. Although there could be many variations on this LSI theme, what is important to note is that the area under the curve represents the government level of effort. Some refer to his role as the "design agent." In the LSI case, this level of effort is more expansive than today and requires new methods, practices, and tools to support the government engineer.

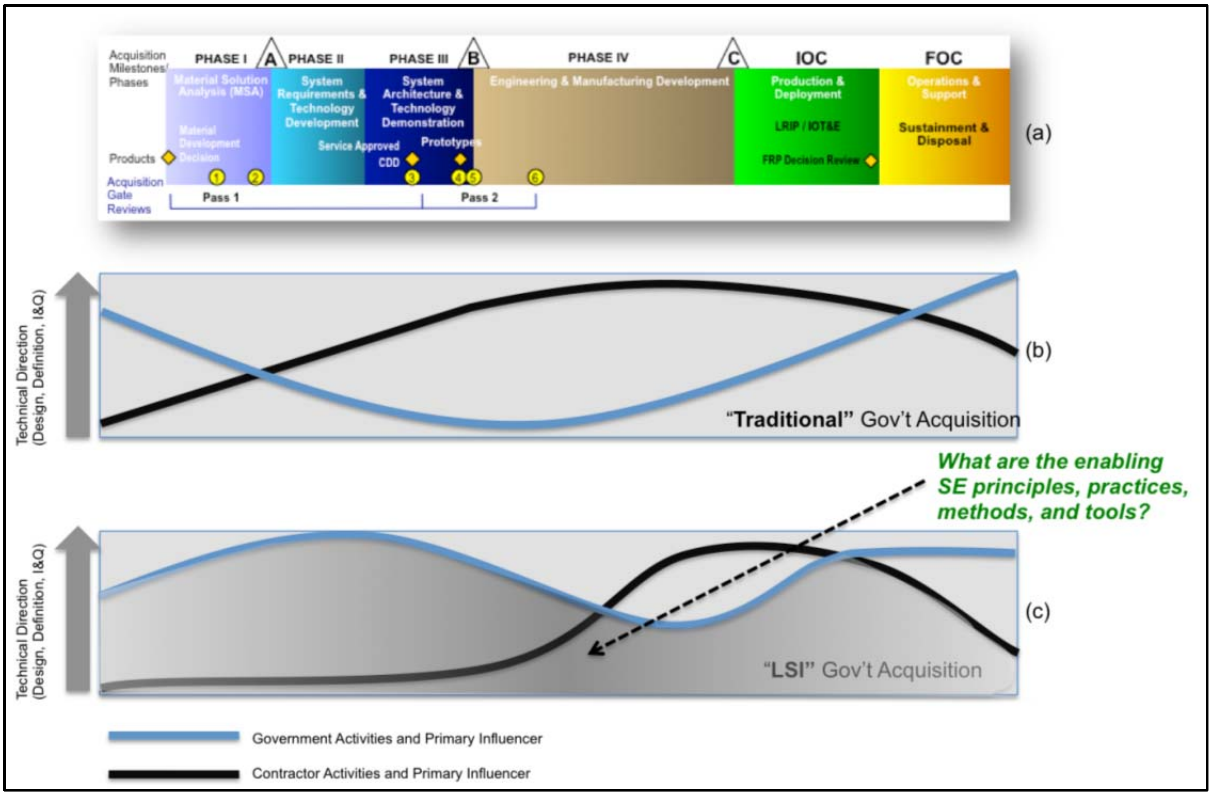

Figure 4. The LSI Roles for the Government—(c) Compared to (b)—Will Require Greater Methods, Practices, and Tools to Achieve Work of the Increased "Area Under the Curve"

Another perspective is to try to assess where the "maturity" of the government engineering community (writ large) is today and how it needs to be enhanced. Figure 5 puts forward a non-scientific assessment of where that maturity may be (dotted line). The colors align with Figure 3 and shows that the current DoD acquisition workforce performs comfortably as a "buyer" and "purchaser", often at the "acquirer" level, but has yet regularly perform at the "architect/designer" or "integrator/LSI" role. The graph shows that, as the government makes the transition to the upper right of the graph, the engineering and programmatic span of authority must, necessarily, increase for the government and decrease for the contracting community.

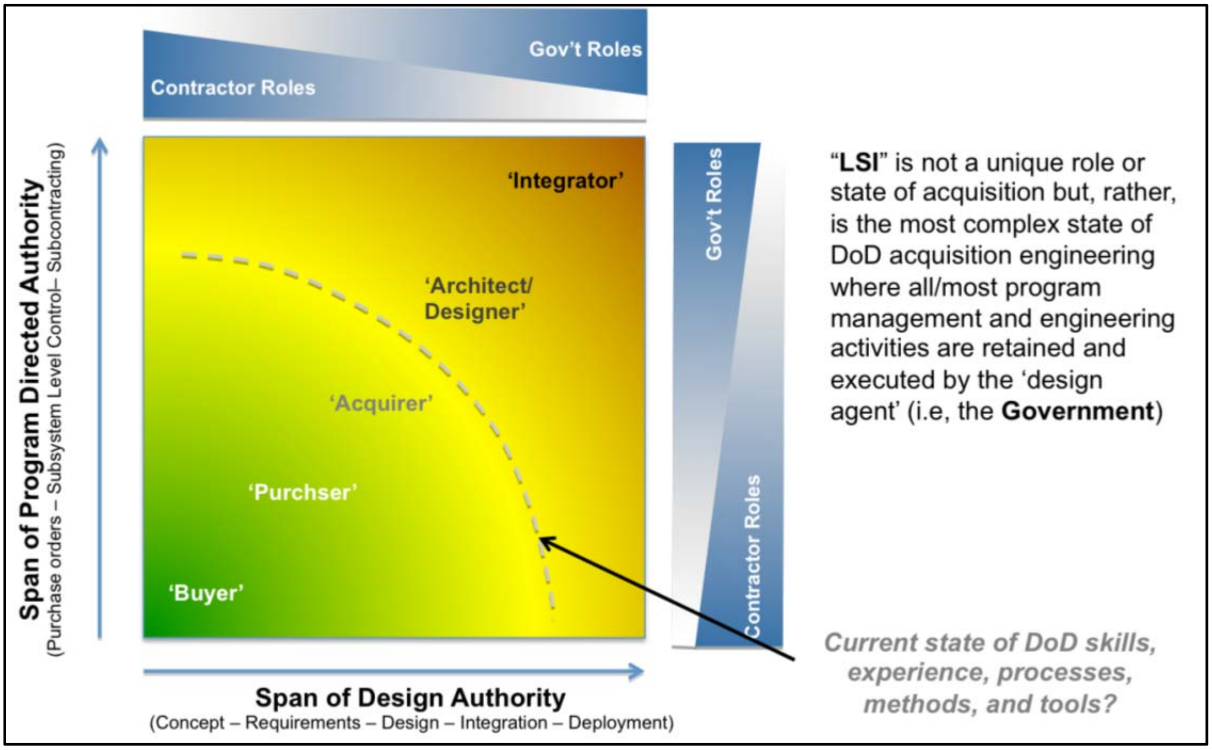

Figure 5. Increasing Role of Government Engineering Toward "Integrator" Will Involve Reducing Span of Design and Programmatic Authority for the Contractor

Systems Engineering Methods Supporting LSI

There are probably very few new fundamental principles and essential activities that are required for the LSI; however, the depth and ownership of SE activities are greater and more enduring. In order for the DoD to move to the upper right-hand corner of Figure 5, additional SE practices, methods, and tools need to be enhanced. A representative SE activity set typically employed throughout any system acquisition cycle is shown in Figure 6. Although we can anticipate that many, if not all, of the activities will be impacted by taking on the role of the LSI, our interviews have indicated that the *early* application of discipline SE practices and methods create the greatest and most significant positive impact to reducing risk and increasing system success. Figure 6 shows that the dark blue activities are the most likely candidates to receive attention for workforce development and to apply SDEA concepts and tools.

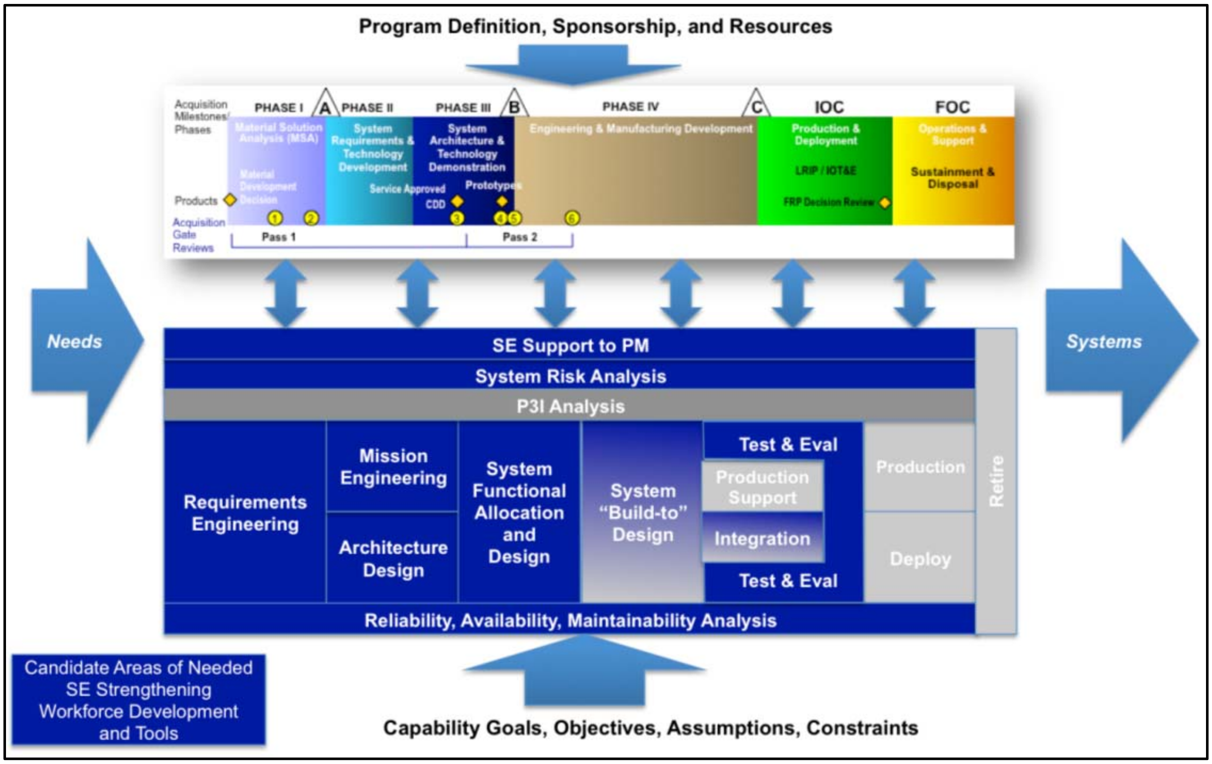

Figure 6. Systems Engineering Activities Need Strengthening to Expand Role as an LSI

Although still formative, the SE activities shown may focus upon general concepts of the following:

- Concept development—Eliminating disconnects between originator needs and acquisition system requirements.
- Design—Inexperience, insufficient or missing tools, and weak methods.
- Integrative methods—Organizational teaming, SoS awareness, standards, priorities, technical incentives.
- Development—DoD (LSI) and contractor common models and tools.
- Integration—Gaps in cross-discipline skills and experience, lack of facilities, weak methods, lack of jointness.
- Test and evaluation—Gaps in attaining a system that is mature and ready for test.

System Definition-Enabled Acquisition (SDEA) System Concept

Top-Level Concept

The top-level SDEA concept is shown in Figure 7. The intent is that SDEA supports all of the SE activities in Figure 6 in a quantitative and repeatable manner. The SDEA system comprises system definition, modeling, and analyses that provide repeatable and quantifiable designs. The SDEA system is to provide a data-driven system definition and model-driven SE approach that supports LSI SE and design.

The SDEA system is synergistic with the program definition, system definition, supportability definition, and system production. Note that all of these activities support

baseline development and control. Program definition leads to system definition and the handoff contract (documents) associated with system capabilities and top-level performance goals.

Additionally, program definition leads to documentation and agreements that set in motion long-term supportability strategies and activities, such as logistics, training and manpower, and long-term supply chain strategies. The SDEA system supports both system definition in a very repeatable and quantifiable manner, as well as providing clear detail and system reliability and supportability metrics to the support system associated with the acquisition.

Finally, system production depends on precise SDEA system definition in order to proceed to production of the system in preparation for deployment.

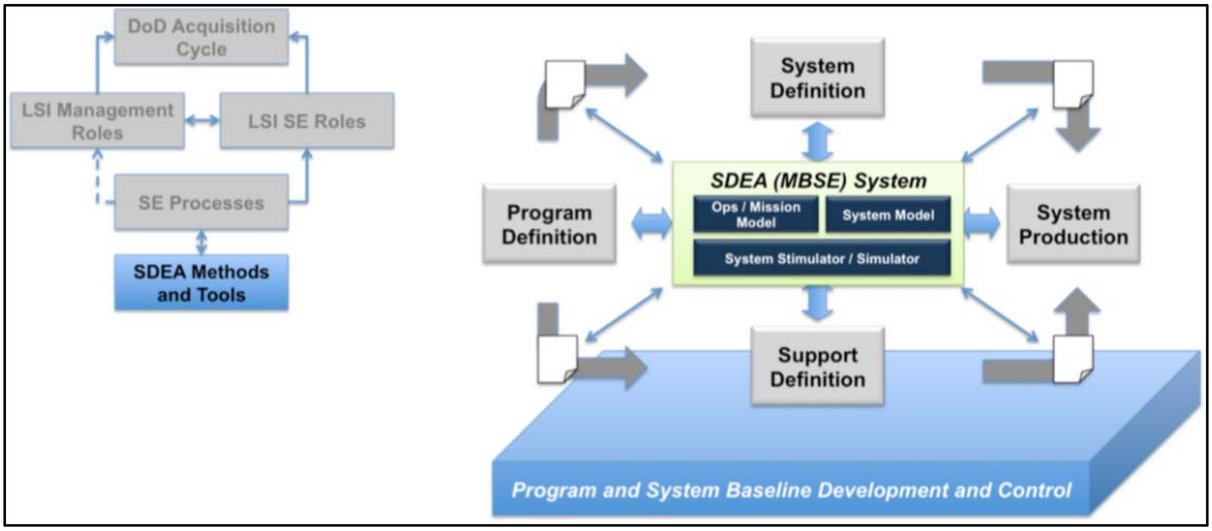

Figure 7. SDEA Provides Central Engineering System Support to Acquisition
(derived from Montogmery et al., 2012)

Summary

Past performance by contractors performing what some now believe are inherently governmental acquisition engineering functions during major DoD weapon system acquisition has proven problematic, in some cases. Legislation and policy is moving DoD to consider transforming its engineering role for major systems (especially SoS) to that of the LSI. The DoD acquisition workforce methods, practices, and tools, however, need to be upgraded and enriched to achieve this transformation. We believe that the integration of model-based system engineering (MBSE) tools through an SDEA method is key to supporting the higher levels of SE design disciplines, analyses, and baseline control, and will contribute to quicker time-to-market and lower integration and interoperability risks for future weapons systems.

In summary:

- An LSI is needed where high system complexity, high risks, or SoS integration/interoperability are present.
- DoD acquisition organizations are exploring taking on more of the LSI roles.
- DoD acquisition practices need fortifying to cope with the more expansive levels of SE.

- SE methods need reinforcing, and SE tools (e.g., SDEA) need to be acquired and integrated into the workflow with capability to provide
    - early and strong SE application (pre-milestone A),
    - data-driven design support tools,
    - repeatable and quantifiable system design analyses,
    - persistent (multi-year/multi-system) design data repository,
    - SoS interoperability and integration analyses, and
    - operational, qualification (V&V), suitability, and sustainability design/analysis support.

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Innovating Naval Business Using a War Game

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Abstract

The Deputy Assistant Secretary of the Navy for Research, Development, Test, and Evaluation (DASN RDT&E) created a Business Innovation Initiative (BII) to identify and overcome challenges presented by the updated Naval Open Systems Architecture (OSA) strategy. The BII seeks to find innovative ways to incentivize Naval program management staff and their industry partners to implement aggressive change measures that improve cost, performance, and time to field for national security systems. The BII conducts workshops and crowd-sourcing activities that focus on specific business impediments to OSA. The Massive Multiplayer Operational War Game Leveraging the Internet (MMOWGLI) game was used as a crowd-sourcing tool to elicit the collective intelligence of acquisition practitioners, students of business, and industry stakeholders to identify and overcome challenges presented by the updated OSA strategy. The MMOWGLI platform provides an efficient mechanism that crosses functional and geographical workspace boundaries for exchanging ideas and forming community in addressing the OSA business problem. The results of the first BII crowd-sourcing event using the MMOWGLI platform are presented in this report.

Introduction

The Assistant Secretary for Research Development and Acquisition (ASN[RDA]) authorized a new Naval Open Systems Architecture (OSA) strategy in November 2012 (see Appendix A) to reduce the total ownership cost of systems, encourage innovation, and more rapidly deliver needed capabilities to the warfighter. This strategy specifically challenges the Naval acquisition workforce to institute measures to improve competition, eliminate redundant developments, and coordinate program activities that promote the reuse of tactical products across sea and air platforms. The acquisition organization is tasked to

implement the strategy, and success will require substantial changes in the Navy's business practices, organizational structures, and resource planning.

In concert with the updated strategy, the Deputy Assistant Secretary of the Navy for Research, Development, Test, and Evaluation (DASN RDT&E) created a BII to search for ways to better incentivize OSA business practices across our current programs of record. Mr. Sean Stackley, ASN(RDA), said in a recent article,

> The value of an innovation initiative is to explore what business relationship changes are needed to open up competition; incentivize better contractor performance; increase access to innovative products and services from a wider array of sources; decrease time to field new capabilities; and achieve lower acquisition and life-cycle costs while sustaining fair industry profitability. (Hudson, 2012)

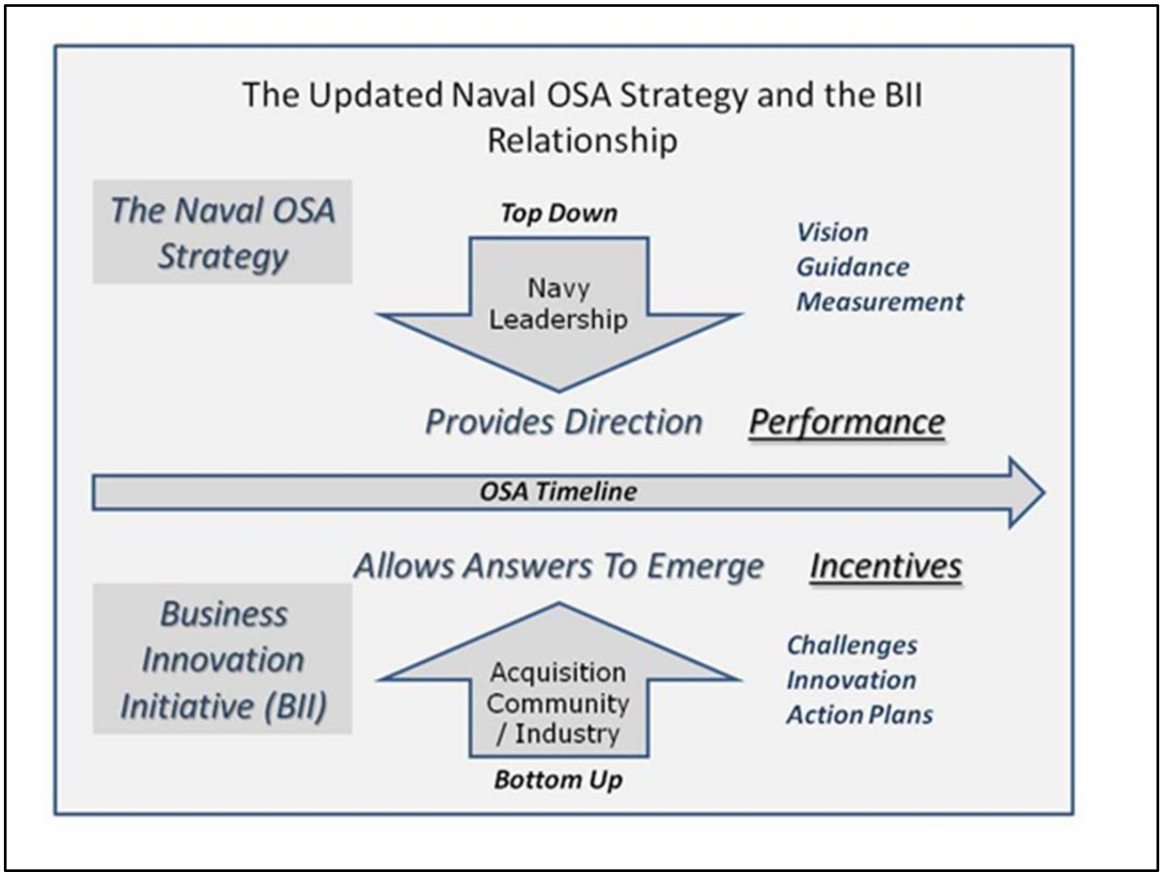

Figure 1. Updated Naval Open Systems Architecture Strategy and Business Innovation Initiative Relationship

As a companion of the updated Naval OSA strategy, the BII examines business operations, processes, and incentives associated with delivering national security systems. DASN RDT&E recognized that using the crowd-sourcing war game facility developed by the Naval Postgraduate School (NPS) presented an opportunity to examine both the OSA strategy and the BII in tandem. Both share activities that could be explored and melded together into a comprehensive set of recommendations on how to advance technical and business changes needed in Naval acquisition.

The BII addresses a two-year plan that will codify methods to rapidly bring innovative capabilities to the warfighter and find a process that seeks continuous cost improvements for initial acquisition, production, and sustainment, while fostering innovation from a broad range of sources.

In the first year, the Naval OSA Enterprise Team (ET) is promoting business models that lower overall cost and ensure a reasonable profit potential, reduce time to market, and remove competitive restrictions. This innovation initiative is looking for reforms that create effective business relationships between government and industry (government-to-business) and between government organizations (government-to-government).

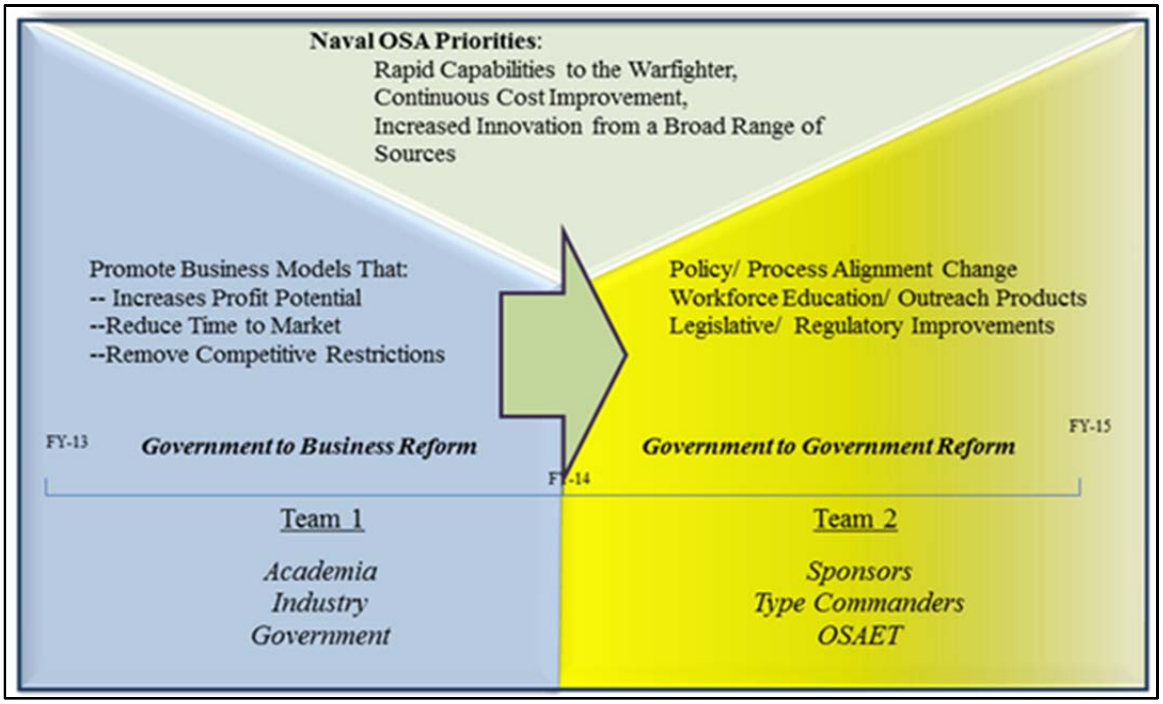

Figure 2. Naval Open Systems Architecture Business Innovation Intiative

Government to Business: In the first year, the government-to-business team is acting to create an open business model framework that recognizes that the defense market is changing and seeks to find opportunities to improve and normalize business relationships. Team 1 consists of academia (top-tier business schools and NPS), industry representatives (strategically formed to have a balanced representation with participation from large and small businesses), and key Department of the Navy (DoN) acquisition staff. The team is scheduled to complete its objectives within 12 months and publish its findings and recommendations to the ASN(RDA).

Government to Government: The second team will complement the work of the first team and will focus on changes that affect the government acquisition community. Team 2 will consist of key representatives from the resource community, the fleet, and the acquisition force (PEOs, SYSCOMs, and laboratories). The team will deliver actionable supporting policies, new procedures, workforce education /outreach tools, and candidate legislative changes.

BII War Games

The term “war game” is used to describe the crowd-sourcing concept exploration events of the BII. The war game is a social networking construct to explore and solve

“wicked problems” (Conklin, 2005) in a large and diverse forum. Wicked problems are those with complex interdependencies where the effort to solve the stated problem may reveal or create other problems. In Naval OSA, for example, a recognized problem is “vendor lock.” Vendor lock is the business principle associated with limited acquisition choice and sole-source contracting and may further be an indication of an unrecognized strategic problem.

The DASN RDT&E selected the Massive Multiplayer Operational War Game Leveraging the Internet (MMOWGLI) as the mechanism to bring innovative concepts from a diverse group together rapidly and effectively. MMOWGLI is an open-source software platform sponsored by the Office of Naval Research (ONR), developed by NPS, and originally designed by Institute For The Future (IFTF). MMOWGLI provides a text-based social networking platform that allows many users to interact directly with one another using web browsers in real time.

The first BII MMOWGLI game was intended to serve as a trial run for understanding whether a crowd-sourcing method for exploring innovations for implementation of the Naval OSA strategy might be valuable and robust. Round One of the BII MMOWGLI game is described in detail in Section 2.

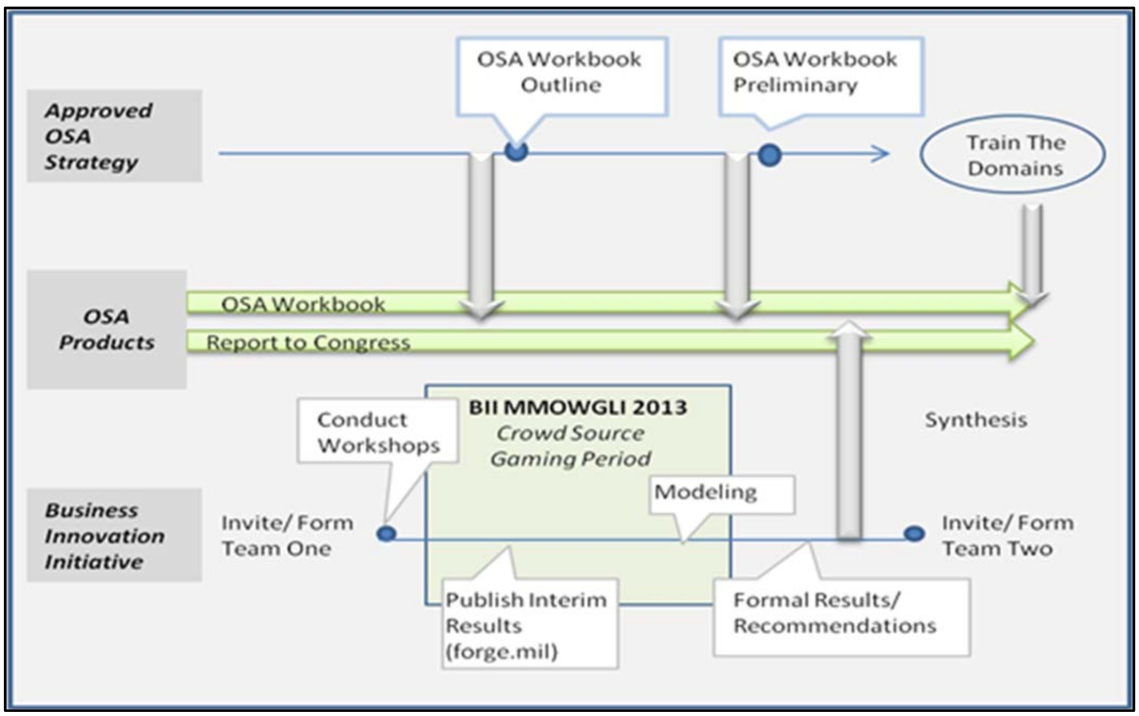

Figure 3. Relative Timeline for Open Systems Architecture/Business Innovation Initiative Interactivities

BII MMOWGLI Game

What Is MMOWGLI?

MMOWGLI is an online game platform designed to elicit collective intelligence from an engaged pool of players to solve real-world problems. MMOWGLI was developed at the NPS’s MOVES Institute under the sponsorship of the ONR. It was launched in 2011. MMOWGLI games have been conducted to look for innovative ideas in a variety of complex problems, including countering international maritime piracy, improving energy efficiency on Navy ships, and several others. Games have also been conducted at a variety of scales (50 to 550 players) and with different audiences (public, industry, Navy, and others).

BII MMOWGLI Round One

War-game design is an important part of the process. The MMOWGLI platform is designed to spur innovation and is highly configurable, but players will not visit or engage unless a clear purpose is evident. Several months of effort went into defining and refining the game themes and prospective audience that might provide the greatest possible impact supporting the overall project goals. A preliminary workshop and a trial mini-game provided excellent feedback regarding what themes were most interesting. Extensive details and the game itself are available online (see BII MMOWGLI Game Portal, n.d.; BII MMOWGLI Game Blog, n.d.; BII MMOWGLI Game Play, n.d.; BII MMOWGLI Game Reports, n.d.).

The DASN RDT&E conducted the first of two planned BII MMOWGLI games for fiscal year (FY) 2013 during the period of January 14 through 28. The purpose of the first round was to test and validate the use of the MMOWGLI crowd-sourcing tool for finding innovation in Naval acquisition and to identify how to use it to find challenges of implementing the updated Naval OSA strategy. Over 100 professionals from government, academia, and industry participated, generating over 890 idea cards and 11 action plans. The first week was dedicated to card play, followed by a second week used for detailed action-plan development.

The Call to Action Statement

Establishing group motivation and common goals is a fundamental prerequisite for an effective war game. The BII MMOWGLI game was introduced to players with this invitation:

> The **BII MMOWGLI game** is for professionals exploring how best to achieve the business goals of the Navy's new "Open Systems Architecture (OSA) Strategy." Your feedback on this plan is welcome.
>
> Round One explores the challenges and opportunities in developing a "Payloads over Platforms" business model driven by the OSA strategy. We are here to discover ways to incentivize acquisition programs and our industry partners to help craft a new business relationship that eliminates redundant development, ensures sustainability of war-fighting capabilities, and positively rewards good industry performance.
>
> Your contributions are essential. Please join in. The BII portal is a great information resource for game play. Check the BII blog for game news. Thanks for your ideas.
> Play the game, change the game.

Card Play

All MMOWGLI games begin with a set of thought-provoking seed cards to initiate discussion. In the BII game Round One, the seed cards were labeled as "challenges." Each challenge card was configured to provide four responses: expand, counter, adapt, or explore. Players would select a response category and type their thoughts in 140 characters maximum, which forced them to be clear and concise with their message. Other players could immediately see that card as part of the discussion chain and be able to select it and respond in kind: expand, counter, adapt, or explore. These linked cards created a chain (or

discussion) where any number of players could contribute. Rules on how to play a particular response card were left to the player's intuition. See Figure 4.

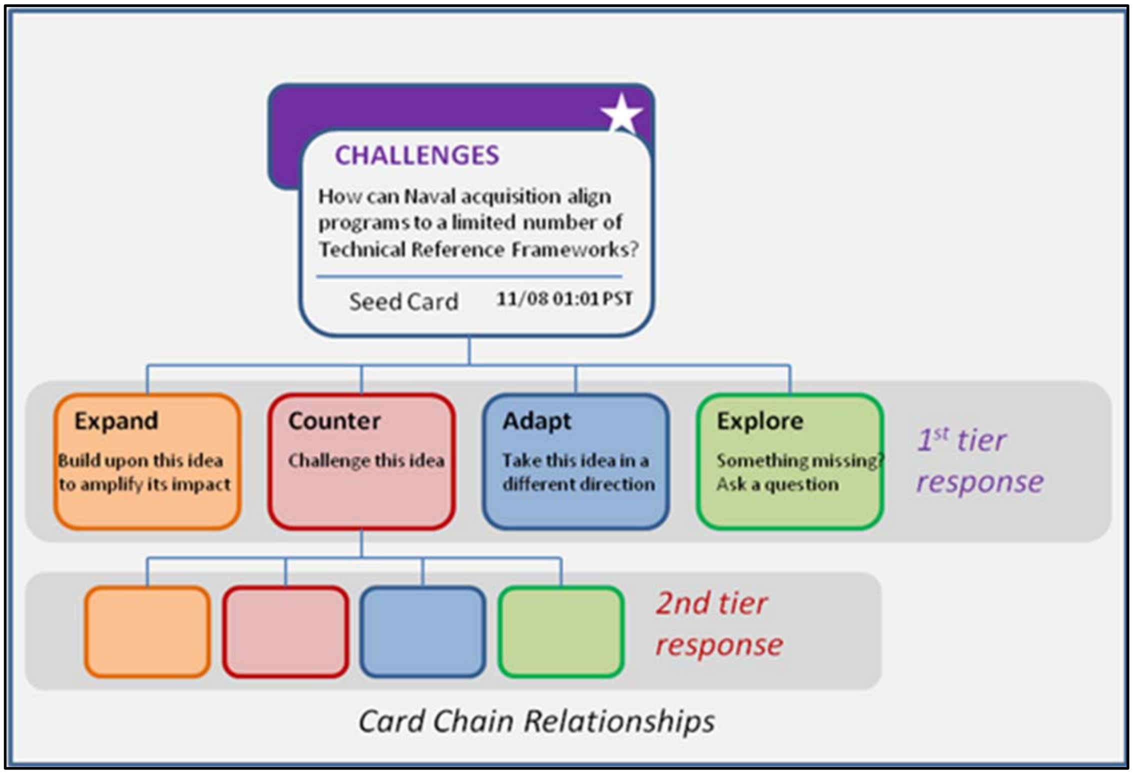

Figure 4. BII MMOWGLI Card Chain Exemplar

Challenge Cards. In our BII MMOWGLI game, seven general questions about the strategy were cast as challenge cards, intended to help players begin conversations of interest. They were as follows:

Challenge Cards:

1. What are the primary challenges of the CNO's "payloads over platforms" strategy?
2. How to incentivize programs and industry to deliver reusable component solutions as an acquisition model?
3. How can we align across programs to eliminate redundant development?
4. How can Naval acquisition align programs to a limited number of technical reference frameworks (TRFs)?
5. Technology conditions change over long service lives of ships and aircraft.
6. Has open architecture (OA) succeeded from a micro perspective and failed in the macro perspective?
7. What do you see as the greatest challenge moving into Phase 1 of the OSA strategy?

An additional set of seven seed cards were also formed under the heading Future Goals. They were "what do you think?" topics intended to stimulate discussion on system acquisition. They were as follows:

Future Goals Cards:

1. How might the acquisition process change to enable more competition by industry: large companies, small companies, and system integrators?
2. How can life cycle management (LCM) improve to avoid “lock in” and enable competition through the long term program?
3. What ships and aircraft are the best exemplar platforms to consider?
4. What Navy programs are the best exemplar payloads to consider?
5. Unmanned systems have much shorter lifecycles, enabling rapid change. How might that improve the acquisition process?
6. How do we define payloads? One person’s payload is another person’s truck…
7. What topic do you want to see addressed in round 2 of the Game next summer? Our theme: *Future Paths Forward For Improved Business Practices.*

Game Play Results

Figures 5 and 6 show the number of player responses for each of the seed cards. Expand and explore cards were most often chosen by the players to amplify on a previous card. Counter and adapt card responses were given much less frequently.

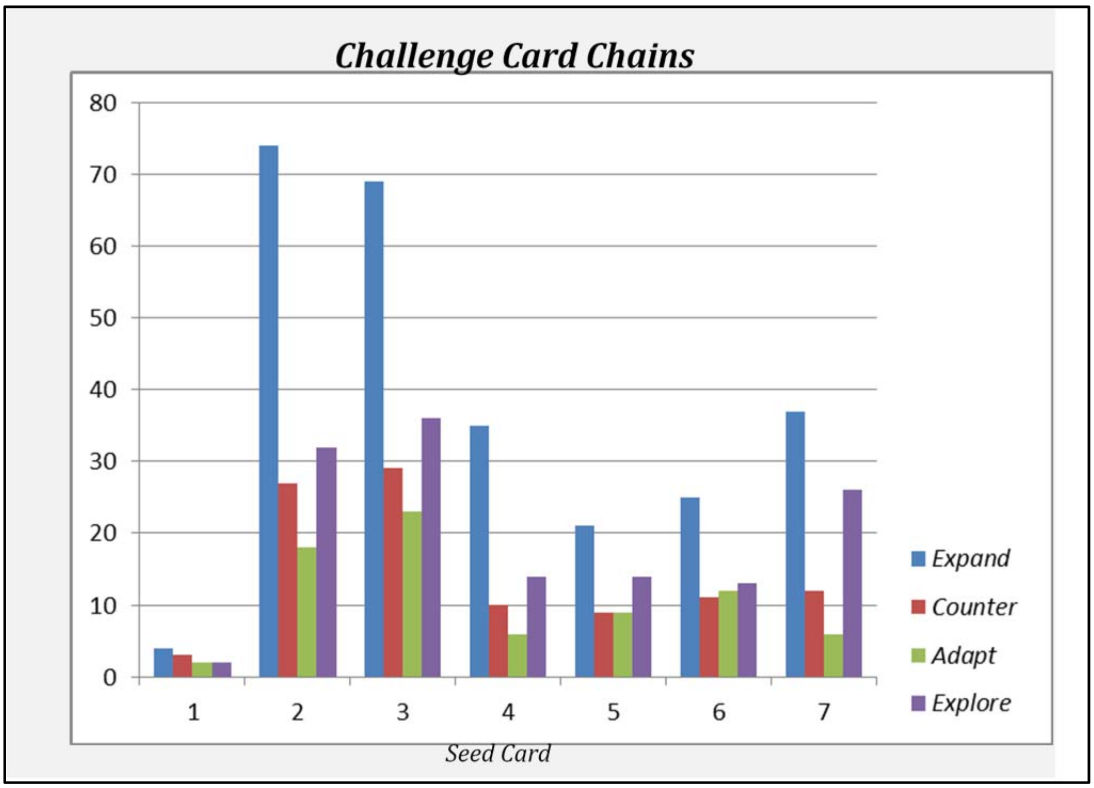

Figure 5. Challenge Card Chains

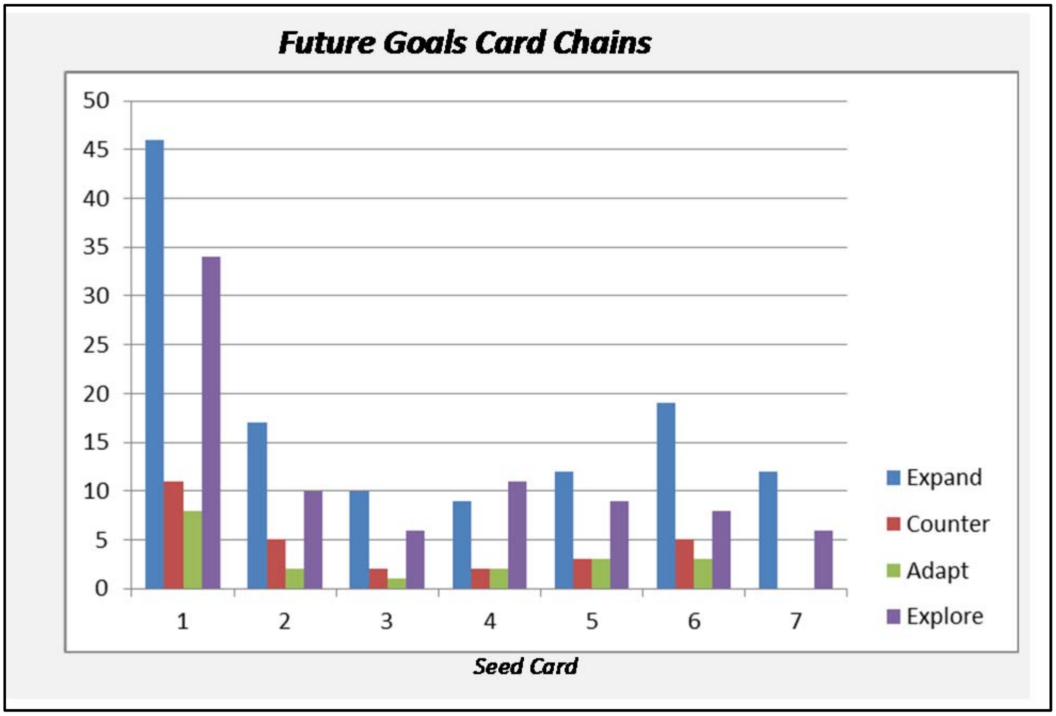

Figure 6. Future Goals Card Chain

Four seed cards generated the most response. It is noted that these cards focused more on Phases 2 and 3 of the OSA strategy.

Challenge Seed Card #2: How to incentivize programs and industry to deliver reusable component solutions as an acquisition model?

Finding ways to incentivize programs and industry to deliver reusable component solutions as an acquisition model generated the second highest interest in the game with 151 total exploration cards played. Today, acquisition programs most often employ effort-based development contracts for a single end user without considering how it might be reused in other programs. A new concept of a “first user–subsequent user” model was offered as a means to include the subsequent user in the acquisition model where vendor savings naturally occur, indicating how the Navy and industry might share benefits of reuse. Conversations focused on data rights, intellectual property, licensing, royalties, and RFP process areas. Industry has the incentive of an expanded market, and government has the incentive of reduced schedule and cost profiles.

Challenge Seed Card #3: How can we align across programs to eliminate redundant development?

This topic drew the highest response in the game with 157 exploration cards played. Program objectives memoranda (POM) roadmaps are a resource management tool that align program funding to the corresponding Future Years Defense Program (FYDP). Financial plans for product line acquisitions were offered as a way to show sponsors that collaboration equals value. These would include first user–future user program budget/schedules as a way to help PEOs and resource sponsors connect the dots.

Challenge Seed Card #7: What do you see as the greatest challenge in executing Phase 1 of the OSA strategy?

One player cited Dr. Gansler's "The Changing Face of Competition," noting that one third of the acquisition workforce has less than five years of experience and does not understand industry operations and incentives. As a result, government relies on a contracting style based more on precedence (i.e., how we do things today rather than how we might do things better). Players focused on the need for specific workforce training for OSA as the greatest challenge to the strategy.

Challenge Seed Card #4: How can Naval acquisition align programs to a limited number of technical reference frameworks (TRFs)?

Citing declining budgets as a motivator, it was noted that some PEOs are starting to coordinate technical frameworks into their plans and programs. Even though PEOs collaborate, there is no technical chain of command, so aligning frameworks becomes a coalition of the willing. Players suggested having the government own their TRFs, so product developers have a stable base to enable broader competition. A counterargument stated that "a limited number should not be the goal since different programs have different needs." This was quickly challenged by another player: "A different need is code for not invented here." The message from this discussion thread is that coordinated TRF design and governance will form a key role in the OSA strategy.

Action Plan Products

Idea card chains quickly illustrate the pros, cons, and alternatives associated with an issue. More is needed when moving beyond improved understanding towards charting possible paths forward and analyzing alternative courses of action.

In MMOWGLI, an action plan is an expansion of an idea formed in game play. It is authored by a small group of players, usually three or four, who collaborate to describe how an idea might work, what the benefits are, and the scope of effort necessary. There are five parts to an action plan (essentially, who, what, where, when, why and how). Below, the "how will it work" section is included as a summary of the plan.

The following five action plans were significant in that they achieved a greater than 66% (two of three possible thumbs-up) voter rating. Players that vote one thumb-up think that the plan is not ready to proceed. Players that give two thumbs-up consider an action plan worthwhile, while players awarding three thumbs-up mean that they think that a plan is especially promising and worthy of further exploration. Here are the top five plans, based on averaged player ratings, from highest to lowest:

Action Plan #10: *How can the Navy use data and software rights to achieve the OSA strategy, ensuring long-term stability and growth?*

<u>How will it work?</u>: Conduct a series of workshops and discussion groups to focus on different perspectives, including how we best leverage the commercial market (while addressing issues and challenges unique to DoD systems) and how we establish a marketplace for reusable applications to reduce cost and increase innovation and interoperability. Result is a spectrum of strategies from which programs can select depending on the reuse potential of specific products in identified markets. Then train the workforce.

Action Plan #3: *Define community of interest (COI) activities and external relationships in the context of the OSA strategy.*

<u>How will it work?</u>: The main catalyst for COIs today is interoperability for mission performance, rather than reuse. The mission area interoperability and integration (I&I) effort should help define systems of systems (SoS) capability gaps. Once people start thinking in

SoS terms, they can start looking at reuse across platforms. That often leads to a homegrown approach and a PARM relationship between programs. PEOs submit capability-based coordinated POM inputs for whole capabilities. The OPNAV coordinates funding decisions so that holistic upgrades are funded.

Action Plan #11: *Streamline OSA contracting to make the process more agile, rewarding innovation.*

<u>How will it work?</u>: Unlike the SBIR program, all efforts would be fully funded, but they would be similar to SBIRs in that they are incrementally funded. Initial awards based on start year (e.g., 2014 base year, with option years 1 … 5). Base-year candidates would be minimally funded with data rights and royalties for reuse, while more mature option year awards would benefit from increased funding. This would push competition for best solutions to win the options as well as the additional royalties.

Action Plan #8: *Outline ROI steps to justify reusing components across participating COI programs.*

<u>How will it work?</u>: An ROI metric would quantify the different ways we save via reuse, including requirements specification, integration, test, training, maintenance, sparing (for H/W), IAVM, and technology refresh. COPLIMO has a COCOMO-based cost model that can look at SW product lines and show where costs are reduced with subsequent reuse by leveraging existing requirements. Also, we need a way to quantify operational benefits from consistency of performance, user interfaces, and more widespread fielding.

Action Plan #6: *How do programs that group together get rewarded for increasing enterprise value?*

<u>How will it work?</u>: In this budget climate, PMs will seek protection, even at the cost of increased program risk, by coupling budget and schedules together. Top leadership direction will be needed to ensure that the reward mechanisms are impactful and consistently applied. Enterprise value must be held to a very high and consistent standard. Accolades must be peer-reviewed. This would have two benefits: the attention to award criteria will rise, and consistency of awards will increase.

Lexical Link Analysis

Results were analyzed independently at NPS using the lexical link analysis (LLA) software-based text comparison tool. LLA compared BII game data to the OSA strategy document and separately to the *Department of Defense (DoD) Open System Architecture Contract Guidebook for Program Managers* (Defense Acquisition University [DAU], n.d.). LLA metrics indicate that the OSA strategy is not considered risky and not particularly controversial, nor is it considered impossible to implement.

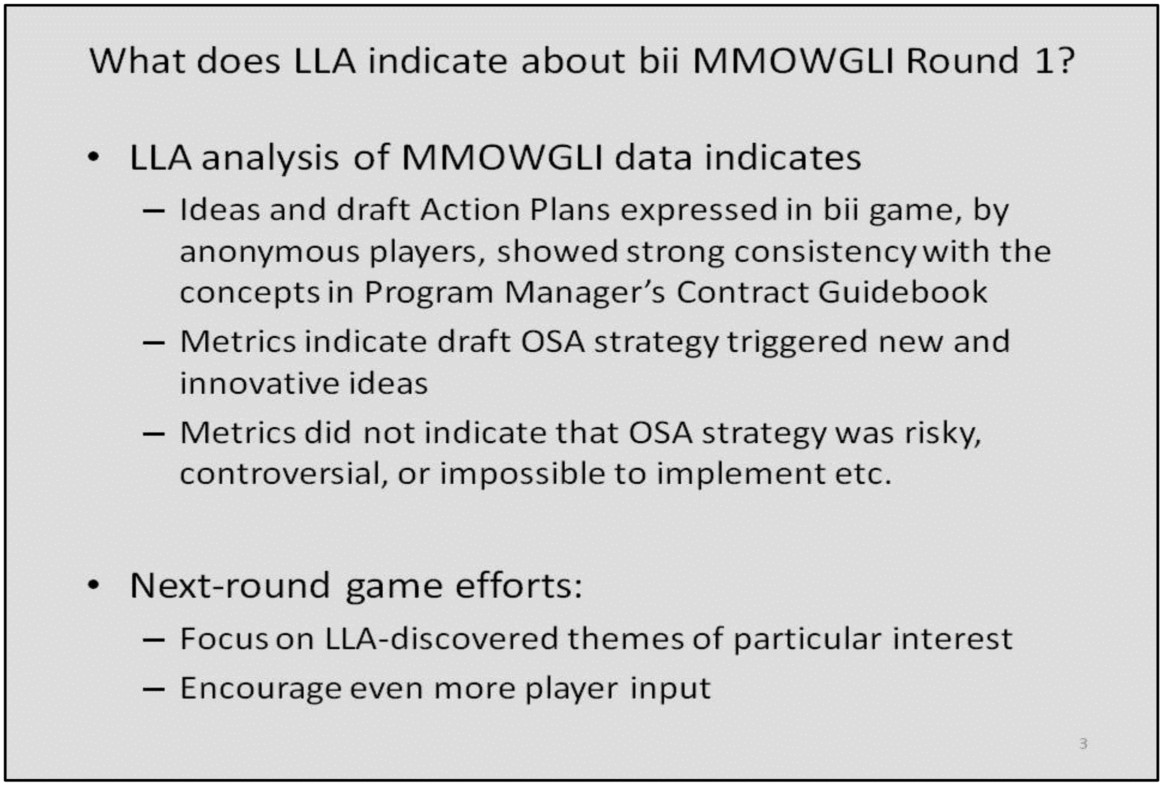

Figure 7. LLA Conclusions, BII MMOWGLI Analysis Report, February 6, 2013

LLA is a form of text-based data mining in which word meanings represented in coupled lexical terms (e.g., word pairs) can be represented as if they are in a community of a word *network*. LLA discovers and displays these networks of word pairs from large-scale, unstructured data. LLA can also be used as a search and knowledge management tool for scoring and ranking interesting information and for visualizing and reporting correlations among categories and layers of information including lexical, semantic, and social links.

This effort then presents the decision-maker with results that were previously unavailable regarding emerging patterns and themes, as well as unprecedented levels of analysis, thus reducing the workload and overcoming the blind spots of human analysts by leveraging automation. For example, for the recent MMOWGLI games used to develop and identify new ideas about a specific subject, LLA was engaged to identify potentially interesting information from idea cards, link them, and then reveal them to domain experts. The methodology of LLA is discussed in more detail in the article in these same conference proceedings (Zhao, Brutzman, & MacKinnon, 2013).

For the BII MMOWGLI project, we performed two separate post-game data analyses.

1. Idea cards (892) and action plans (11) were compared to the proposed OSA strategy (four pages) considered by players.
2. Idea cards (892) and action plans (11) were compared to the *Department of Defense (DoD) Open System Architecture Contract Guidebook for Program Managers* (158 pages) already familiar to most players.

What did LLA indicate about BII MMOWGLI Round One? LLA data analysis indicates the following:

- Ideas and draft action plans expressed in the BII game by anonymous players showed strong consistency with the concepts in *Department of Defense (DoD) Open System Architecture Contract Guidebook for Program Managers*.
- Metrics indicate that draft OSA strategy triggered new and innovative ideas.
- Metrics did not indicate that OSA strategy was risky, controversial, nor impossible to implement.

LLA also discovered eight main or popular themes listed, reflecting common interest of the players, using the following keywords:

- multiple support and components
- common data, data model
- component reuse, OSA
- open system and business
- systems architecture, current systems
- specific price and fee
- existing reusable programs
- engineering, government, and community

We also found innovative ideas (i.e., gaps between the game data and the OSA strategy document) in the following areas (themes):

- small and shared based
- developed and built faster
- critical definition
- specific price and fee
- sponsors change and risk
- changing requirements
- interoperability and interfaces

Figure 8 shows one example theme detailed from the comparison of game data with the OSA strategy document. Red nodes show the top three word hubs with most links (most “central”). Yellow word pairs are unique to the action plans, green word pairs are unique to the ideas cards, and blue word pairs are unique to the OSA strategy document. Red word pairs are found in more than two sources.

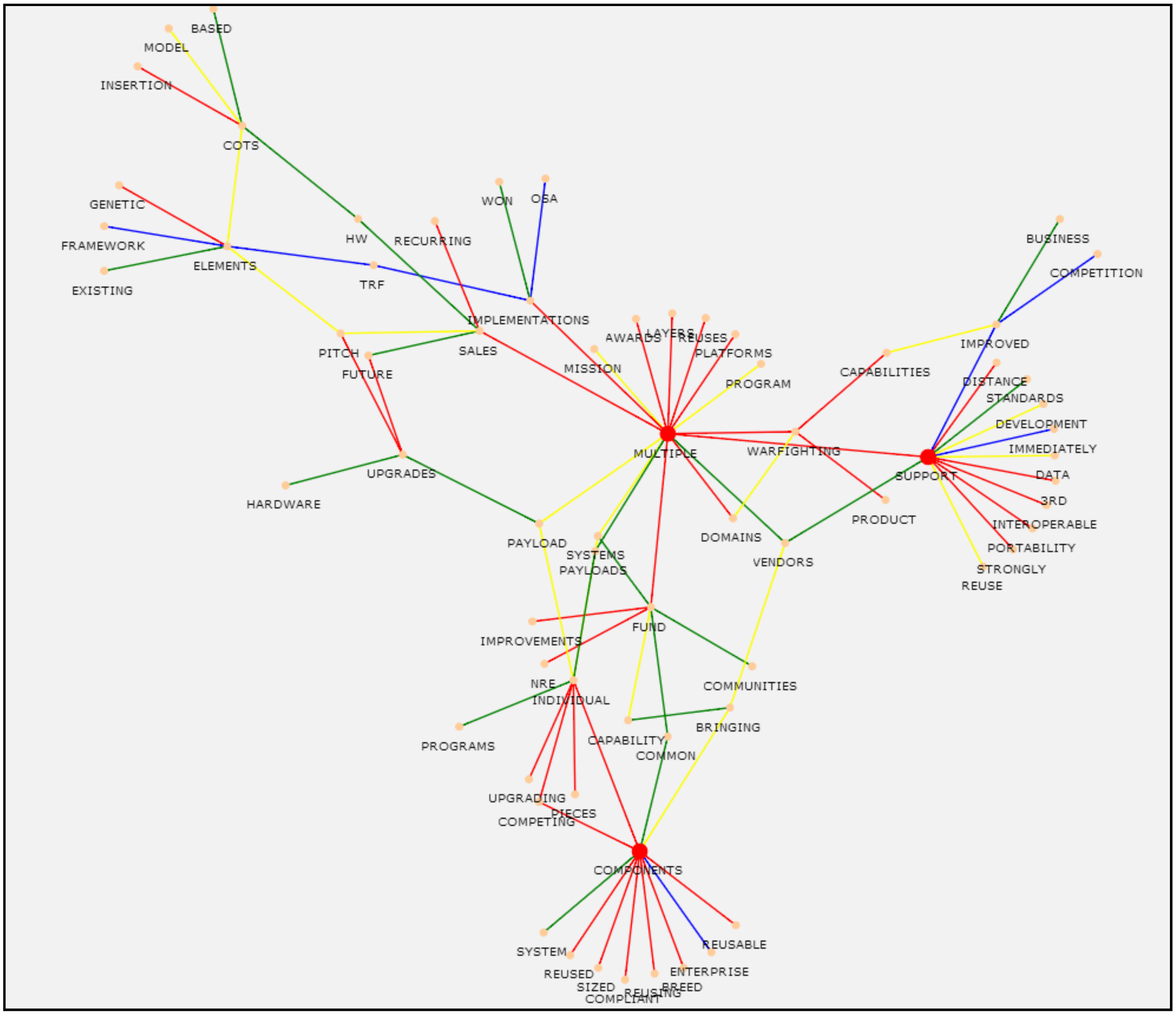

Figure 8. One Theme Detailed From the Comparison of the Game Data With the OSA Strategy Document

Note. Red nodes show the top three word hubs with most links (most "central"). Yellow word pairs are unique to the action plans, green word pairs are unique to the ideas cards, and blue word pairs are unique to the OSA strategy document. Red word pairs are found in more than two sources.

Subject-matter expertise is necessary to determine whether statistically generated concepts have real relevance and interest. Based on the concepts, themes, and gaps discovered in BII Round One, analysts compiled and distilled a list of 20 candidate topics for possible seed card exploration in BII Round Two. One example is shown as follows, using the theme illustrated in the preceding figure and centered around the keywords *multiple-support* and *components.*

- How will the concept of TRF addressed in the strategy document be enhanced from the ideas surrounding "multiple support and components," a COTS-based model?
- Relevant concepts from Round One: Network-based COTS (Idea Card Chain 850), COTS hardware (Idea Card Chains 138, 89), COTS insertion (Idea

Card Chain 770), COTS model (Action Plan 4), and COTS elements (Action Plan 10)

The reason emerging concepts such as this can be generated is that salient ideas emerge from commonality and differences between data corpus comparisons, allowing expert analysts to discern which topics might hold the greatest interest.

A number of reports and analytic products are generated by the game. To reap the maximum benefits from the contribution of so many focused ideas and plans, post-game analysis is an important activity that helps find the most valuable conclusions and also results in products of greatest value to past (and future) participants.

Lessons Learned

Round One Results Exceeded Expectations. The DASN RDT&E expected that BII MMOWGLI Game Round One would generate a list of challenges for the updated OSA strategy. Players instead concentrated their activities on identifying ways to make the strategy successful. It was clear that they viewed their role as problem solvers rather than problem identifiers. This is a valuable lesson for planning Round Two of the BII MMOWGLI game. Understanding a player's natural motivation to create ideas on challenges gives the planning team a better understanding of how to select and "seed" the topics for consideration in the next round of play.

Crowd Sourcing Builds Community. An unexpected benefit from using this tool was the aspect of community building. Those who played BII MMOWGLI Game Round One formed a diverse team with different points of view. Game players were anonymous and used a made-up player name to engage in discussions. The anonymity provided a shield from intimidation or prejudice, in that all seemed open to the ideas and comments of others and willing to engage in debate on the pure basis of the issues, rather than taking an industry or government positional argument. Players expanded their ideas using a game feature called action plans, inviting other players to help them author potential solutions … and it worked. The lesson learned here is to open the problem set to the widest audience possible. Opinions and interactions ultimately come together to build the views of a larger community.

Enlisting a Broad Audience Requires Promotion and Advertising. BII MMOWGLI Game Round One was as much about testing the tool as it was about getting direct, actionable results. As such, marketing was minimal. E-mail invitations shortly ahead of the event and a few public announcements formed the ad campaign. Current members of the OSA ET, BII academic partners, and selected industry partners who volunteered to participate at the Defense Daily Open Architecture Summit of October 2012 formed the main body of invitees. In response to approximately 900 e-mail invitations, just over 100 people played.

Conclusions

The success of the new Naval OSA strategy relies on the Navy acquisition community's ability to cross program boundaries and work together toward common goals. We can take full advantage of the power of community by using focused information technology. MMOWGLI has proved to be an effective mechanism to improve communication and coordination among the various program offices, program executive offices, and systems commands. The DASN RDT&E considers the BII MMOWGLI Game Round One a success for the following reasons:

1. The use of MMOWGLI to explore Naval OSA challenges exceeded expectations. The players of the BII war game identified several innovations on how to implement the Naval OSA.
2. Game play supported the intent of the BII to explore the business relationships changes to (a) open up competition, (b) incentivize better contractor performance, (c) increase access to innovative products and services from a wider array of sources, (d) decrease time to field new capabilities, and (e) achieve lower acquisition and life-cycle costs while sustaining fair industry profitability.
3. Those who played BII MMOWGLI Game Round One formed an enthusiastic group with different points of view, highlighting the power of crowd sourcing to build a diverse community around topics of mutual interest.

Multiple recommendations for future work are now being pursued as the team prepares for BII MMOWGLI Round Two. Our motto remains: Play the game, change the game!

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Appendix A

O•S•A Open Systems Architecture *Strategy*

Introduction

The current Naval Enterprise acquisition model is centered on highly integrated platforms with systems that are largely vendor locked, and expensive to acquire and upgrade. This model is especially problematic in the current economic environment.

The Naval Open Systems Architecture (OSA) strategy will decompose monolithic business and technical designs into manageable product lines composed of competition-driven modular Enterprise components. This will yield innovation, reduced cycle time, and lower total ownership costs.

The New Naval Enterprise OSA Strategy:

The Naval OSA Strategy is an iterative set of business and technical changes that points to an end state where affordable, open platforms easily accommodate open modules. As the Navy moves toward this future, the Enterprise must first align itself to become open, modular, common, competitive, and ultimately, affordable. It will begin by implementing change in a coordinated fashion across all programs.

The Naval OSA Enterprise Team will lead the execution of this strategy with the participation of stakeholders (e.g., Resource Sponsors, PEOs, TWAs, etc.) as follows:

- Implement the coordinated set of business changes that improve competition, incentivize better performance, and deliver capability more rapidly;
- Construct a limited number of technical reference frameworks to immediately support improved competition and ultimately enable enterprise re-use;
- Develop an Execution Guidebook for this strategy; and
- Lead and guide training the workforce on OSA implementation.

Once these changes have been adopted at the program level, a second iteration (Figure 1) will prepare the Enterprise to eliminate redundancy and deliver open systems with reusable modules.

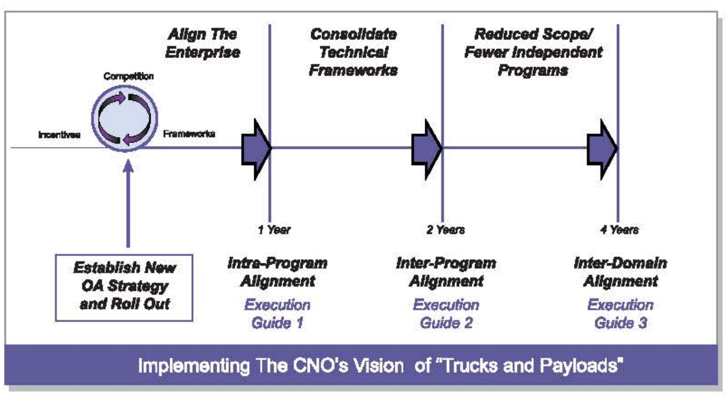

Figure 1. Iterative Naval OSA Strategy

Open Systems Architecture (OSA) Strategy 1

An Open Systems Architecture (OSA) approach integrates business and technical practices that yield systems with severable and compete-able modules. A system constructed in this way allows vendor-independent acquisition of warfighting capabilities, including the intentional creation of inter-operable Enterprise-wide reusable components. Successful OSA acquisitions result in reduced total ownership cost and can be quickly customized, modified, and extended throughout the product life cycle in response to changing user requirements.

Naval OSA Strategy Actions

Unless otherwise stated, the principal lead for the following actions is the Open Systems Architecture Enterprise Team (OSAET), led by Deputy Assistant Secretary of the Navy (Research, Development, Test and Engineering) (DASN RDT&E), with participation from Systems Commands (NAVSEA, NAVAIR, SPAWAR, and MARCORSYSCOM), program Executive Offices (PEO), the Office of Naval Research, and designated Communities of Interest (COIs).

Phase 1: *Align current programs to execute the OSA strategy and report progress.*

Phase 2: *Consolidate technical frameworks across programs; eliminate redundant stovepipes.*

Phase 3: *Implement Enterprise architecture of modular development and maximum reuse.*

Phase 1 Tasks

- Establish a limited number of OSA Technical Reference Frameworks (TRFs);
- Change acquisition processes to adopt these coordinated and common OSA TRFs;
- Require and incentivize competition throughout program life cycles;
- Establish meaningful metrics to assess OSA progress;
- Develop the OSA Strategy Execution Guidebook;
- Educate the Naval Engineering, Logistics, and Acquisition Workforce; and
- Codify knowledge, skills and processes in the "OSA Program Managers Guidebook, rev 1.0"

Phase 2 Tasks

Tasks for phase 2 are TBD; here are a few categories:

- Communications processes to provide transparency across PEOs and SYSCOMS about existing programs
- Incentives for collaboration and cooperation
- Funding techniques for cross-Enterprise co-development
- Update the "OSA Program Managers Guidebook"
- Build on education efforts through DAU and integrate the new Guidebook with standing courses

Phase 3 Tasks

Tasks for phase 3 are TBD; here are categories:

- Fine tune communications processes to provide transparency across PEOs and SYSCOMS about existing programs, as needed
- Adjust incentives for collaboration and cooperation as needed
- Add courses to fill needed knowledge gaps
- Adjust funding techniques for cross-Enterprise co-development

O·S·A

Establish a Limited Number of Technical Reference Frameworks (TRFs)

A Technical Reference Framework (TRF) is an integrated set of components that provide a reusable architecture for a family of related applications. TRFs should be capability-based to maximize employment and capability insertion on multiple platforms. Limiting the number of TRFs will increase interoperability and reuse opportunities, leading to life cycle cost savings.

Maintaining non-duplicative TRFs will require cooperative interaction and create interdependencies across program boundaries. TRFs are dynamic so will continue to evolve as technology dictates. Configuration management and attribute/characteristic alignment processes will be crucial TRF enablers. To develop and maintain TRFs, the Naval Enterprise shall take the following steps:

1. Analyze existing system TRFs and develop a detailed set of proven Enterprise attributes, including standardized specifications, architectures, data models, interoperability protocols, and software development tools;
2. Catalog features and suitability for a variety of platform types;
3. Promote tailor-able open standards relative to TRF attributes;
4. Coordinate cross-program TRF implementations to reduce duplication through transparency;
5. Identify, publish, and manage TRF elements necessary to move programs to coordinated product lines and S&T investments using enterprise-level TRF attributes; and
6. Require PEOs and Systems Commands to use TRFs for all development unless explicitly waived by ASN (RD&A).

Change Acquisition Processes to Adopt OSA TRFs

Changes must be made to current Naval acquisition processes to allow Enterprise adoption of OSA TRFs. The Naval Enterprise shall take the following steps:

1. Charter cross PEO groups and Communities of Interest (COIs) through Program Management Offices (PMOs) to steer the development of common TRFs, applications, and testing strategies;
2. Identify best practices and collaborative forums to increase the likelihood of transitioning maturing technology into programs of record;
3. Change guidance, procedures, and instructions to require preference for OSA implementation and systematic reuse for cost savings across system life cycles; and
4. Insert OSA into the System Engineering Technical Review (SETR) and acquisition program Gate Review processes.

Require and Incentivize Competition throughout Program Life Cycles

The Navy values innovation and lower costs at all acquisition phases (i.e., concept development, design, build, maintenance and upgrade) and system levels (i.e., component, system, platform, and system of systems). The Naval Enterprise shall take the following competition-focused steps:

1. Create contract language templates for use in contract solicitations at the platform, integrator, system, and component levels;
2. Develop tools and methods to promote competition at the component level and to objectively measure the openness of development environments;
3. Require Program Managers to evaluate movement away from monolithic acquisitions to multiple, modular acquisitions enabled by OSA;
4. Require Program Managers to secure and exercise data rights needed to ensure future competition for sustainment, maintenance, and capability insertion; and
5. Establish reward mechanisms for programs and personnel successful in achieving OSA implementations that rapidly integrate innovation and lower total ownership costs.

ASN-RD&A

Establish Meaningful Metrics to Assess Progress

Development and adoption of metrics that are objective, readily obtained (ideally from existing sources), easy to interpret, and actionable to enforce desired behaviors (i.e., increased competition, component reuse and reduced costs) are vital to the OSA strategy. The Naval Enterprise shall take the following steps to implement an OSA metrics program:

1. Establish a set of metrics for use in assessing the Enterprise value of new capabilities;
2. Pilot these metrics to selected COIs/Programs of Record (PORs) from each domain;
3. Update metrics based on these pilots for application across the Naval Enterprise;
4. Implement an Enterprise metrics program and conduct periodic peer review assessments on a sampling of PORs from across the Enterprise; and
5. Identify patterns of strengths and weaknesses in Enterprise OSA implementation and apply remediation throughout program life cycles.

Develop the OSA Strategy Execution Guidebook

The Execution Guidebook will contain actionable steps for each implementation phase of the OSA strategy. It will contain recommended changes in the business model and technical framework elements that will begin by improving competition and ultimately result in fewer programs that cost less and deliver capability more rapidly.

Educate the Naval Engineering, Logistics, and Acquisition Workforce

The success of the OSA Strategy depends heavily on a competent, innovative, and well educated workforce. The Naval Enterprise must produce a workforce that is well-versed in: identifying and managing cross-domain and life cycle dependencies, understanding and responding to adverse vendor behaviors, ensuring that competition yields the desired results, and incorporating OSA best practices as an integral part of program management. The Naval Enterprise shall take the following steps to develop an OSA workforce:

1. Target timely OSA training and communication to optimize acquisition program adoption;
2. Develop training and communication materials, leveraging existing training materials, use cases, and delivery mechanisms when possible;
3. Establish OSA transparency mechanisms to enable the acquisition workforce to become aware of opportunities for collaboration;
4. Work with the Defense Acquisition University (DAU) to develop an Acquisition OSA Qualification Standard;
5. Develop training materials and methodologies to train the non Defense Acquisition Workforce Improvement Act (DAWIA) Naval workforce involved in engineering, logistics, and program management; and
6. Establish an OSA mentoring program for acquisition professionals.

Computer-Aided Process and Tools for Mobile Software Acquisition

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Abstract

Mobile devices have, in many ways, replaced traditional desktops in usability, usefulness, and availability. Many companies are scrambling to develop enterprise strategies to provide mobile devices and application support for their employees, and the DoD is taking the point in the federal government's campaign to deploy mobile devices. A successful DoD mobile software acquisition program requires efficient and effective means to assure the proper functioning of the applications. As the majority of future mobile apps will be developed by small companies (or crowdsourcing individuals) and have relatively short development cycles, a traditional software verification process that relies on the testing of source code is not effective for vetting mobile apps. The paper presents a new approach for vetting mobile software. It allows subject matter experts to specify desirable and undesirable behaviors of the mobile apps as executable statecharts and to verify the target software by running the automatically generated statechart code against the execution trace of the mobile apps using log file–based runtime verification. A case study of formally specifying, validating, and verifying a set of requirements for an iPhone application that tracks the movement of the iPhone user is used to demonstrate the new approach.

Introduction

In an April 23, 2012, blog post, analyst Frank E. Gillett of Forrester Research predicted that "tablets will become our primary computing device" in the near future, with "global tablet sales to reach 375 million units, with one-third purchased by businesses and two-fifths (or 40 percent) by emerging markets" by 2016 (Gillett, 2012). Many companies are scrambling to develop enterprise strategies to provide mobile devices and application support for their employees, and the DoD "is taking the point in the federal government's campaign to deploy mobile devices" (Kenyon, 2012a). The Defense Information Systems Agency (DISA) has opened a program office and issued a request for information to solicit ideas from industry for ways to provide the mobile device management (MDM) services and to run an applications store (Kenyon, 2012b), and the Army has established the Army

Software Marketplace, a prototype online storefront for Army-wide distribution of mobile software.

As the DoD is charging forward with its mobile programs, it must find ways to address its concerns in security, authentication, and logistics in managing and deploying the rapidly growing number of mobile applications and devices with varying degrees of access across the DoD enterprise. The Space and Naval Warfare (SPAWAR) Atlantic System Center is working with DISA and the National Institute of Standards and Technology (NIST) to provide warfighters with access to unclassified information from their handheld devices via the cloud-based mobility-as-a-service, and the recent adoption of a hardened kernel for the Android mobile operating system is another major step towards providing a secure base for the development of trustworthy mobile software. Moreover, the DoD needs an efficient and effective process to ensure the proper functioning of the mobile software (commonly referred to as mobile apps), so that the software does what it promises to do and does so without hidden or emergent malicious behaviors.

Mobile apps shrink the software programs that were once only available on a desktop computer, making them usable on smart phones and mobile devices. The app market has been growing at an unprecedented rate. The app world, which consisted of 8,000 Apple titles in 2008, had reached 1 million titles in 2011 (Freierman, 2011). As the majority of mobile apps are developed by small companies (or crowdsourcing individuals) and have relatively short development cycles, traditional software verification processes that rely on testing of source code are not effective for vetting mobile software. The DoD needs better means to ensure the proper functioning of mobile apps without source code or other detailed information about the software's implementation.

This paper presents a new approach for vetting mobile software. It allows subject matter experts to specify desirable and undesirable behaviors of the mobile apps as executable statecharts and to verify the target software by running the automatically generated statechart code against the execution trace of the mobile apps using log file–based runtime verification.

The rest of the paper is organized as follows. The V&V of Mobile Apps section provides a summary of the current state of verification and validation (V&V) of mobile apps. The Formal Specification and Validation of Mobile Apps section presents an overview of statechart assertions, our formal specification language of choice, and the proposed computer-aided process for the V&V of mobile apps. The section Case Study presents a case study involving the formal specification, validation, and verification of a set of requirements for an iPhone application that tracks the movement of the iPhone user. The last section is the conclusion, which provides a summary and draws some conclusions.

The V&V of Mobile Apps

Verification and Validation (V&V) is a software evaluation process to ensure proper and expected operation. As stated in Michael, Drusinsky, Otani, and Shing (2011),

> Verification refers to activities that ensure the product is built correctly by assessing whether it meets its specifications. Validation refers to activities that ensure the right product is built by determining whether it meets customer expectations and fulfills specific user-defined intended purposes.

Simply stated, the purpose of V&V is to ensure the software does what it is required to do, and nothing more.

Difficulties in Testing Mobile Apps

New mobile devices, especially phones, have such short development times that the devices have barely been on the market long enough to work out existing bugs before the new device with new software is ready to release. As an example, Apple releases a new iPhone model every year, and has developed six generations of iOS. The Android operating system had eight versions in three years. This high turnover of mobile devices is created not only by demand and competition, but also capability increases of computing power, battery life, and screen size. As new capabilities are added to the devices and applications in each development cycle, new automated V&V techniques are needed to keep up with the fast pace of mobile application development.

Additional difficulties in the testing of mobile applications are due to limitations of the hardware. At this time, other than operating system tasks, iPhone can only run a single application at a single point in time. The purpose is to conserve the limited computing power of the device as well as reduce power consumption. The negative aspect is that there is little or no application interaction on a single device. This prevents useful testing applications from running on mobile devices to analyze the real-time behavior of applications. Even if such an ability were possible, the small screen size would create difficulties in analyzing the data while on the device. Android devices have the ability for third-party developers to create multiprocessing applications, which could allow analytics to be conducted directly on the device, but the same screen size limitation would impede analysis of the data (see Muccini, Francesco, & Esposito [2012] for a detailed discussion of the challenges in testing mobile apps.)

These limitations make testing done off the device more amenable. There are two possible options: use device-specific emulators, or use specially altered software code to allow offloading of real data from the device onto a computer for analysis. While the emulators will do a good job creating a proper environment to test an application, it has the limitation of being stuck in place, and does not recreate the ever-changing environment in which mobile devices exist. The other method could potentially include such a robust environment; the currently existing techniques require a cable connection to a computer, tethering the mobile device to an immobile one. The current techniques also require an instrumented version of the original code to provide a mechanism to offload the required information to properly evaluate the operation of the application.

Current Solutions to V&V of Mobile Apps

Monkeyrunner enables the writing of unit tests to test software at a functional level ("Monkeyrunner," n.d.). Monkeyrunner uses Python to run testing code on one or more devices, or an emulator. It can send commands and keystrokes, and record screenshots. Monkeyrunner allows for the repetition of test results, but element location in the recorded screenshots is the basis for comparing two test results. This limits comparisons to a single screen size.

Android Robotium is a Java-based tool for writing unit tests ("User Scenario Testing," n.d.). Similar to Monkeyrunner, it is designed to run as a black-box testing tool and can run as an emulator, as well as run on the actual device, although it is limited to a single device. Robotium allows for testing of pre-install software as well. The big difference between Robotium and Monkeyrunner is that Robotium has a more robust test result comparison. Rather than using a location-based method, Robotium uses identifiers to recognize elements. This allows devices of different types and sizes to be compared to ensure consistency.

Lesspainful.com provides a way for customers to run software and unit tests on physical devices without the cost of owning the devices (Lesspainful Device Lab, n.d.). The customers use the programming language Cucumber to write an English description of the test they would like to run on their software. Once the devices to be tested on are chosen, the tests are automated in a cloud-like system with results from each mobile device presented to the customer to allow for easy comparison.

Testquest 10 is a software suite, created by Bsquare, which enables unit tests in a device emulator and enables the collaboration of geographically dispersed teams (Bsquare, 2003). It utilizes an extensive use of image recognition to determine device state as well as the location of applications and features on the screen. An interesting feature is that if the GUI design is changed and an application or feature is moved from one location to another, this suite is able to locate and use the feature.

Bo, Xiang, and Xiaopeng (2007) introduced an approach for testing a device and software by using what they called sensitive-events. Their approach reduces the need for screenshot comparisons by capturing these events, such as inbox full, to determine state change. The software will then evaluate these state changes and, if the events indicate desired conditions, the tests will continue.

All of the aforementioned software tools are for testing an application to ensure proper functionality and operations. What they are missing is the ability to map the operation of the phone directly to a set of requirements. The above tools all require some form of script writing, which can lead to missing software test cases. When writing scripts to cover unit tests, the programmer must understand the requirements and determine boundary (edge) cases in order to properly test for them. The tools are also limited in their ability to handle context-aware features. Another limitation is that, due to the limitation of the hardware and the software testing suites, only one application at a time can be tested.

Delamaro, Vincenzi, and Maldonado (2006) used an extension to the JaBUTi, called JaBUTi/ME. The extension takes JaBUTi, which is a Java byte code analysis tool, and adds the ability to run instrumented-code on a mobile device that creates trace data, and then pass the trace data to a desktop computer for analysis. By using a method of creating trace data, this solution is conceptually similar to the idea presented in this paper. However, this method still requires test cases to be manually written to evaluate the resulting trace file. Additionally, as stated by the authors, the code instrumentation would vary based on the hardware device the code is being tested on. This is due to the potential differences in network connectivity needed to transmit the trace data back.

Formal Specification and Validation of Mobile Apps

Michael et al. (2011) pointed out that

> Software engineers have become competent at verification: we can build portions of systems to their applicable specifications with relative success. However, we still build systems that don't meet customers' expectations and requirements. This is because people mistakenly combine V&V into one element, treating validation as the user's operational evaluation of the system, resulting in the discovery of requirement errors late in the development process, when it's costly, if not impossible, to fix those errors and produce the right product.

Hence, first and foremost, we need a means for analysts to describe the desirable and undesirable behaviors of the mobile apps. Typically, the requirements-discovery process begins with constructing scenarios involving the system and its environment. From

these scenarios, analysts informally express their understanding of the system's expected behavior or properties using natural language and then translate them into a specification. Specification based on natural language statements can be ambiguous. For example, consider the following requirement for a project management software: The software shall generate a project status report once every month. Will the software meet the customer's expectation if it generates one report each calendar month? Does it matter if the software generates one report in the last week of May and another in the first week of June? What happens if a project lasts only 15 days? Does the software have to generate at least one report for such a project?

Research has shown that formal specifications and methods help improve the clarity and precision of requirements specifications (Easterbrook et al., 1998). However, formal specifications are useful only if they match the true intent of the customer's requirements. Because only the subject matter expert (SME) who supplied the requirements can answer these questions, the analyst must validate his or her own cognitive understanding of the requirements with the SME to ensure that the specification is correct. For example, consider the security requirement R1: *If there are more than two invalid logins within any 15-second interval, then the mobile device will remain unavailable for 10 minutes.* Whether the scenario shown in Figure 1 violates R1 depends on the interpretation of the starting time of 10-minute timeout interval.

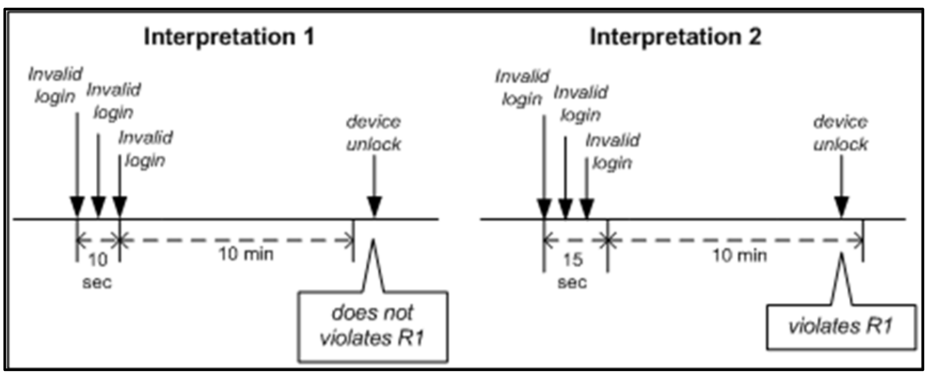

Figure 1. Example of Requirements Ambiguity

The best way to validate and disambiguate complex behavioral requirements is to walk through the different scenarios with the stakeholders and ask them to confirm or clarify the requirements analyst's cognitive understanding of the natural language requirements. Drusinsky, Shing, and Demir (2007) proposed the iterative process for assertion validation shown in Figure 2. This process encodes requirements as Unified Modeling Language (UML) statecharts augmented with Java action statements and validates the assertions by executing a series of scenarios against the statechart-generated executable code to determine whether the specification captures the intended behavior.

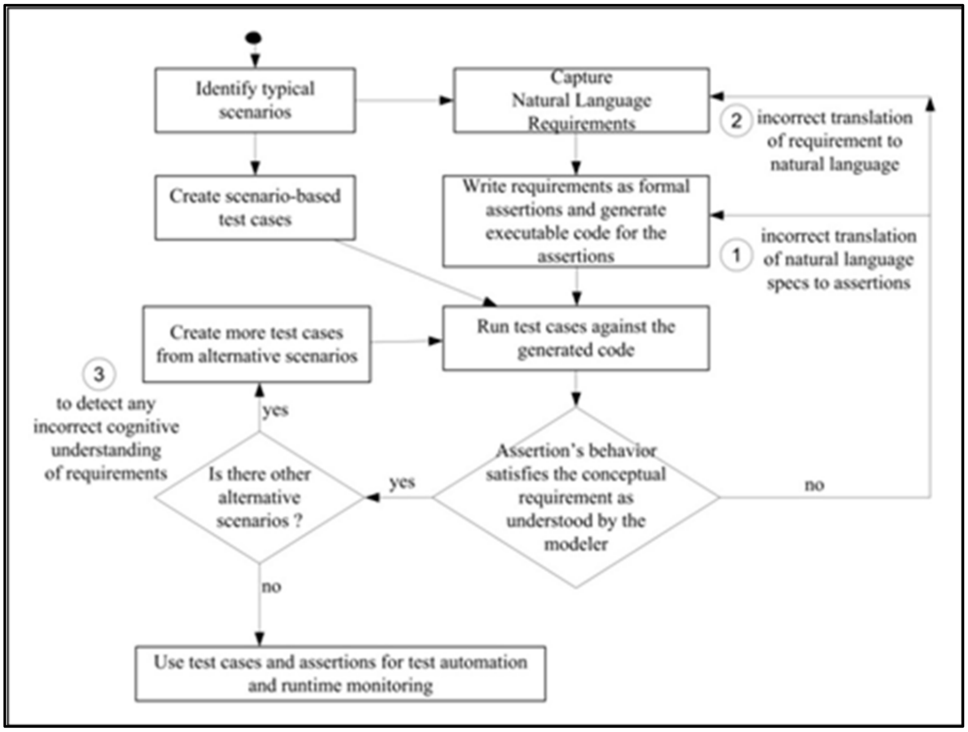

Figure 2. Iterative Process for Assertion Validation
(based on Drusinsky, Shing, & Demir, 2007)

Statechart Assertions

A statechart assertion is a UML statechart-based formal specification for use in prototyping, runtime monitoring, and execution-based model checking (Drusinsky, 2011). It extends the Harel statechart formalism (Harel, 1987) and is supported by StateRover, a plug-in for the Eclipse integrated development environment (IDE; see www.timerover.com/staterover.pdf). StateRover provides support for design entry, code generation, and visual debug animation for UML statecharts combined with flowcharts.

The statechart assertion extends Harel statecharts by adding a *bSuccess* Boolean flag and by enabling non-determinism. Statechart assertions are formulated from an external observer's perspective. Though the *bSuccess* Boolean is a simple mechanism, it is instrumental in determining if an assertion ever fails. The Boolean indicates whether the assertion was violated by the system being analyzed. A statechart assertion assumes the requirement it is based on is met (*bSuccess* = true), and it will retain that assumption unless a sequence of events leading to the violation of the requirement specified by the statechart assertion is observed. Once an assertion fails (i.e., reaches an error state), *bSuccess* becomes false and will stay false for the remainder of the execution. Since the statecharts are simple, it is easy to identify the assertion that failed and the cause.

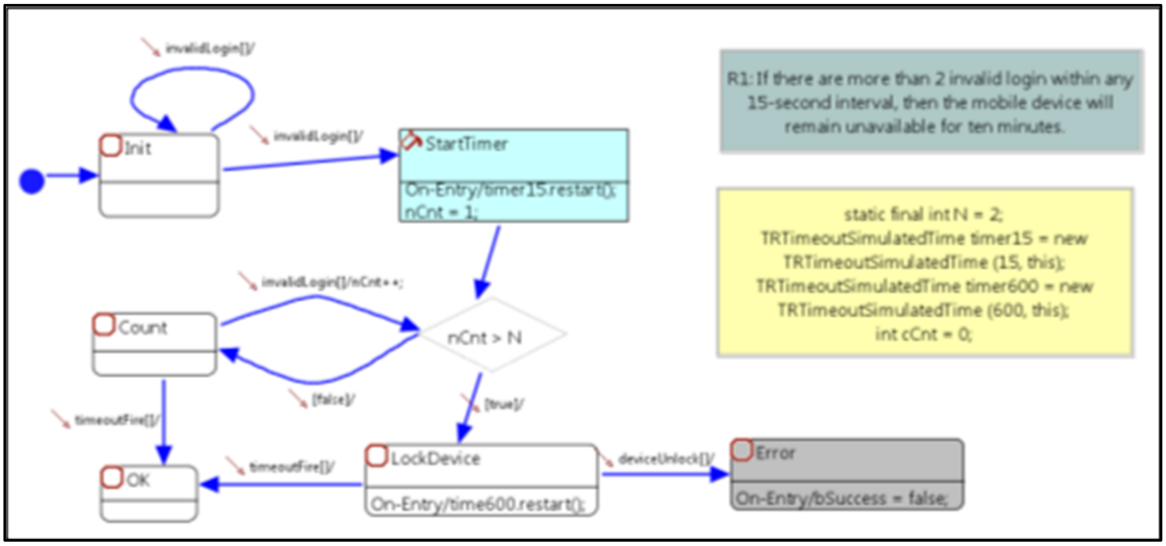

Figure 3. A Statechart Assertion for Requirement R1

Figure 3 shows a statechart assertion for the requirement R1, where the 10-minute interval starts immediately at the detection of the third *invalidLogin* event within a 15-second interval according to the analyst's interpretation of the natural language requirement. The statechart is written from the standpoint of an observer, who is interested in the proper sequencing of two system events: *invalidLogin* and *deviceUnlock*. It uses two timers to keep track of the timing constraints in R1. Starting out in the *Init* state, the statechart transitions to the flowchart-action box *StartTimer* when it observes an *invalidLogin* event. It increments the counter *nCnt* and starts the 15-second timer, and then checks to see if the counter *nCnt* exceeds 2. If *nCnt* ≤ 2, it enters the *Count* state. Whenever the statechart observes an *invalidLogin* event in the *Count* state, it increments the counter *nCnt* and then checks to see if the counter *nCnt* exceeds 2. The statechart will remain in the *Count* state until either the 15-second timer expires, or until *nCnt* > 2. If *nCnt* > 2, the statechart enters the *LockDevice* state and starts the 10-minute timer. The statechart will remain in the *LockDevice* state until either the 10-minute timer expires, or until it observes a *deviceUnlock* event. It the statechart observes a *deviceUnlock* event in the *LockDevice* state, it enters the *Error* state. The entry action for the *Error* state sets *bSuccess* to false, meaning that the requirement R1 has been violated.

The StateRover supports the specification of complex requirements using non-deterministic statecharts. While deterministic statechart assertions suffice for the specification of many requirements, theoretical results show that non-deterministic statecharts are exponentially more succinct than deterministic Harel statecharts (Drusinsky & Harel, 1994). Non-deterministic statechart assertions provide a very intuitive way for designers to specify behaviors involving a sliding time window. In the statechart assertion shown in Figure 3, there is an apparent next-state conflict when an event *invalidLogin* is observed in the *Init* state. StateRover uses a special code generator to create a plurality of state-configuration objects for non-deterministic statechart assertions, one per possible computation in the assertion statechart. Non-deterministic statechart assertions use an existential definition of the *isSuccess* method, where if there exists at least one state-configuration that detects an error (assigns *bSuccess* = false), then the *isSuccess* method for the entire non-deterministic assertion returns false. Likewise, terminal state behavior is existential; if at least one state configuration is in a terminal state, then the non-deterministic statechart assertion wrapper considers itself to be in a terminal state.

For example, the statechart assertion in Figure 3 will generate four state-configuration objects for the test scenario shown in Figure 4 at runtime, one for each *invalidLogin* event. The state-configuration object that starts with the second *invalidLogin* event will end up in the *Error* state, causing the *isSuccess* method to return false to the test driver.

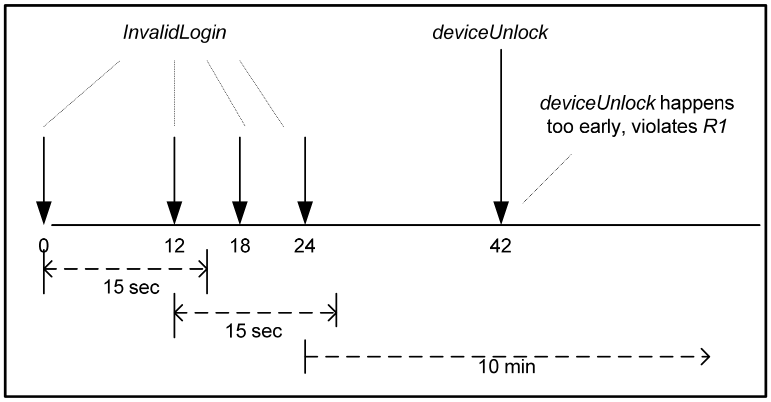

Figure 4. An Exception Test Scenario for the Statechart Assertion R1

Validation of Statechart Assertions

StateRover's Code generator generates a Java class R1 for the statechart assertion file. The generated code is designed to work with the JUnit Java testing framework (Beck & Gamma, 1998; see Figure 5).

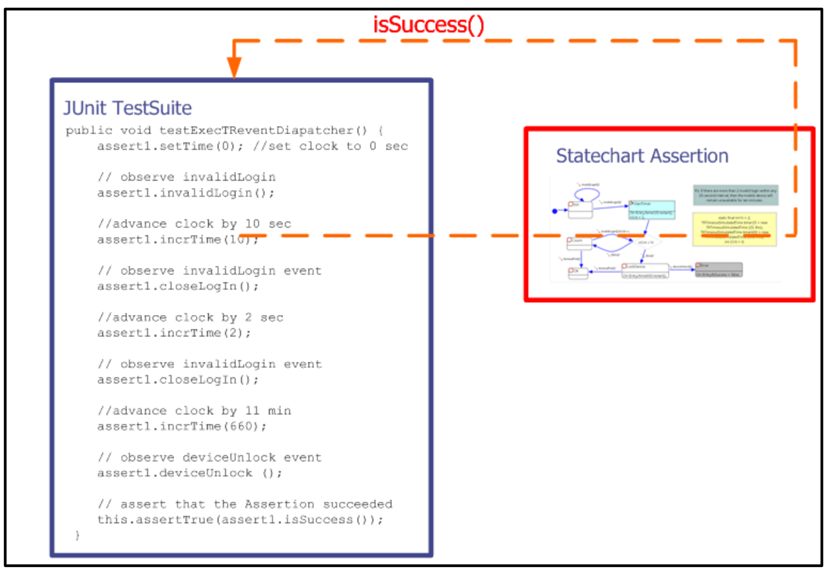

Figure 5. Validating Statechart Assertion via Scenario-Based Testing

To assure that the statechart assertion works as specified in R1, we test its behavior using the JUnit test cases corresponding to the different scenarios shown in Figure 6 and the one shown in Figure 4.

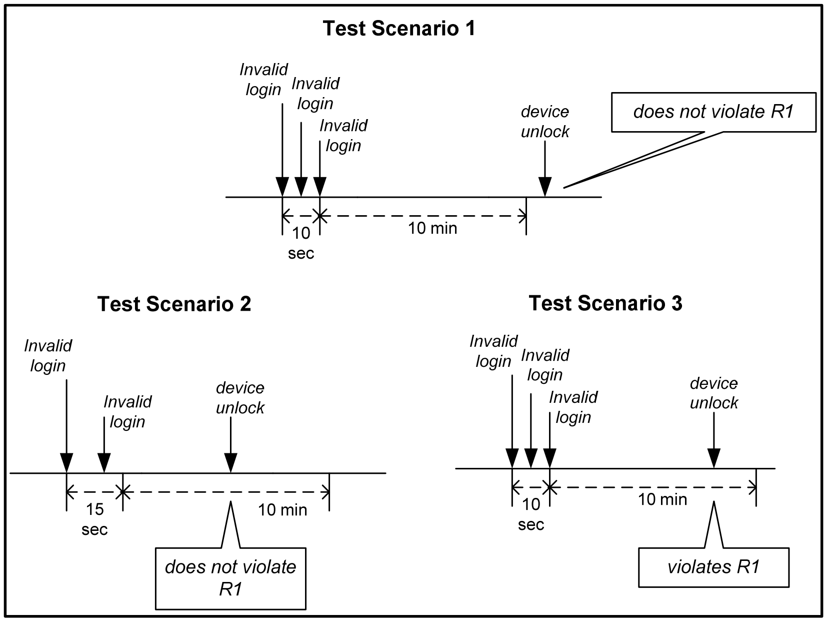

Figure 6. Test Scenarios for the Statechart Assertion R1

Test Scenarios 1 and 2 in Figure 6 represent two typical “happy” scenarios. Test Scenario 1 expects the system to detect the three *invalidLogin* events within a 15-second interval and then lock the device for 10 minutes. Test Scenario 2 expects the system to keep the device open since it only observes two *invalidLogin* events within a 15-second interval. Test Scenario 3 represents an exception scenario, where the system allows the device to be unlocked too early, causing the statechart assertion to enter the *Error* state, thereby signaling that the assertion detected a requirement violation.

Log File–Based Runtime Verification of Mobile Apps

Alves, Drusinsky, Michael, and Shing (2011) presented an end-to-end process that begins with a system requirement as a natural language specification, followed by the creation and computer-aided validation of UML statechart-formal specification assertions, and ending with the log file–based runtime verification of the target system. These log files were executed as JUnit tests against the assertions. They applied the process to the specification, validation, and verification (SV&V) of the critical time-constrained requirements of the Brazilian Satellite Launcher flight software, and uncovered several inaccuracies in the requirements understanding and implementation.

Computer-Aided Process for the V&V of Mobile Apps

We shall apply similar process to conduct the V&V of mobile apps, which consists of the following steps:

1. Subject matter experts determine the properties of interest and the metrics to verify/measure those properties in the lab.
2. The properties are then expressed precisely as statechart assertions, whose correctness is validated via runtime verification.
3. The mobile devices and applications are then instrumented, if needed, for data collection and log file generation.
4. The instrumented codes are deployed to the field via mobile apps downloads. Metric data are collected in log files while the mobile devices are being used

in the tactical environment, and the log files are uploaded back to the lab while the mobile devices are being recharged.

5. The log files are then converted into JUnit tests, and the tests are run against the statechart assertions in the lab. The test results are analyzed and reported.

Using log files produced by mobile apps brings two benefits: (1) it captures the behavior of the application on an actual, physical device and (2) the data contained in the file will represent the behavior of the application as it executes. Log files collected by the application in execution on a device that is fully mobile hold data that is representative of the expected normal operation of the application. Therefore, we can analyze the log files to determine if the behavior was correct based on the requirements. As demonstrated in the next section, we do not need to instrument the mobile device or its software if the events of interest are derivable from the output data of the mobile apps.

Case Study

The case study involves a smartphone application that uses a GPS to track the location and speed of a person in motion. A log of the collected GPS data must be kept in the smartphone until it can be uploaded to a server via a Wi-Fi connection. GPS applications can consume a lot of power and storage space and since mobile devices have limited amounts of both, minimizing the consumption of both is important.

Due to the limited available storage space on the mobile device, we must minimize the amount of GPS data stored. The method chosen to accomplish this is to adjust the rate at which the GPS updates occur to be based on the speed at which the user is traveling. An additional requirement is that the log file must be able to be transmitted from the device to a server by a Wi-Fi connection only. This is because many of the users will not have wired connectors for the devices. If at any point Wi-Fi connectivity is lost and there is an active transmission, it must be terminated. The application has a limit of 30 seconds to transmit the log file, after which, if not successful, the user must be notified of the failed transmission within five seconds. Additionally, a log file must not be transmitted within one hour of a previous log transmission. Both the use of a time-limited transmission window for the log file as well as an infrequent upload of the log file will aid in reducing the amount of power and bandwidth the application consumes.

Specification and Validation of the Statechart Assertions

When a user is traveling at a slow speed like walking, frequent updates are unnecessary because significant distance changes do not happen quickly. If the user is traveling at a faster pace, then more updates allow for more consistent tracking. When the user is traveling at less than or equal to two meters per second, the application should average five seconds or more per update. This is approximately the walking speed of a human (Carey, 2005). If the user is traveling at greater than two meters per second, but less than or equal to five meters per second, then there must be an average of between two and five seconds between updates. This is considered running speed. If traveling greater than five meters per second, then there must be an average of less than two seconds between updates. This is driving speed.

We decided to use an average of seconds between updates due to the typically less-than-accurate GPS data provided by mobile devices. A requirement for an average over a minimum of five GPS update events will be included to reduce the effects of any lack of precision in the GPS data from the mobile device. Table 1 lists the requirements.

Table 1. Speed-Based Requirements

Speed Category	Average Speed (x) in meters per second	Expected Time between Updates (y) in Seconds per Update
Walking	x<=2	5<=y
Running	2<x<=5	2<=y<5
Driving	5<x	y<2

Drusinsky, Michael, and Shing (2007) stated that a model-based specification that uses a single, intertwined representation of the software requirements (e.g., as a single statechart) can become complex and difficult to understand due to the interaction of each requirement with others. They advocated the use of assertion-based specification, which allows the requirements to be decomposed into their simplest forms, and then create a formal representation (e.g., a statechart assertion) for each requirement. This decomposition allows a one-to-one connection between a statechart assertion and a customer requirement. A significant benefit of this connection is that it simplifies the development, analysis, and testing of the statechart assertions. Other benefits include the following:

1. Reduction of the statechart assertion complexity: Since the complexity of the statechart assertions is minimized, the statechart assertions are much easier to test for correctness.
2. The one-to-one connection between a statechart assertion and a customer requirement simplifies the changes that need to be made to the assertions when the requirements change.
3. Statechart assertions can be made to represent a test for both negative and positive behaviors, whereas a model-based specification usually only captures positive behaviors.
4. Tracing unexpected behaviors to the one or more requirements that they violate is simpler because there is a one-to-one mapping.

Hence, we refine the speed-based GPS Update requirement into three requirements. Figures 7, 8, and 9 show the statechart assertions for each of the three speed categories of the speed-based GPS Update requirement.

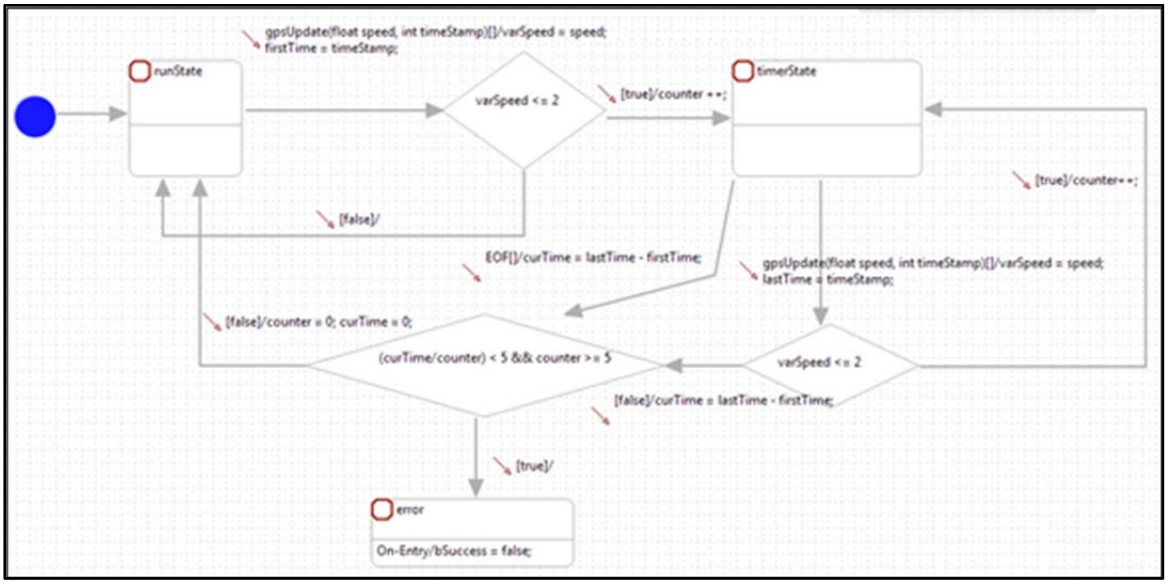

Figure 7. Statechart Assertion for Speed Less Than or Equal to 2 Meters per Second

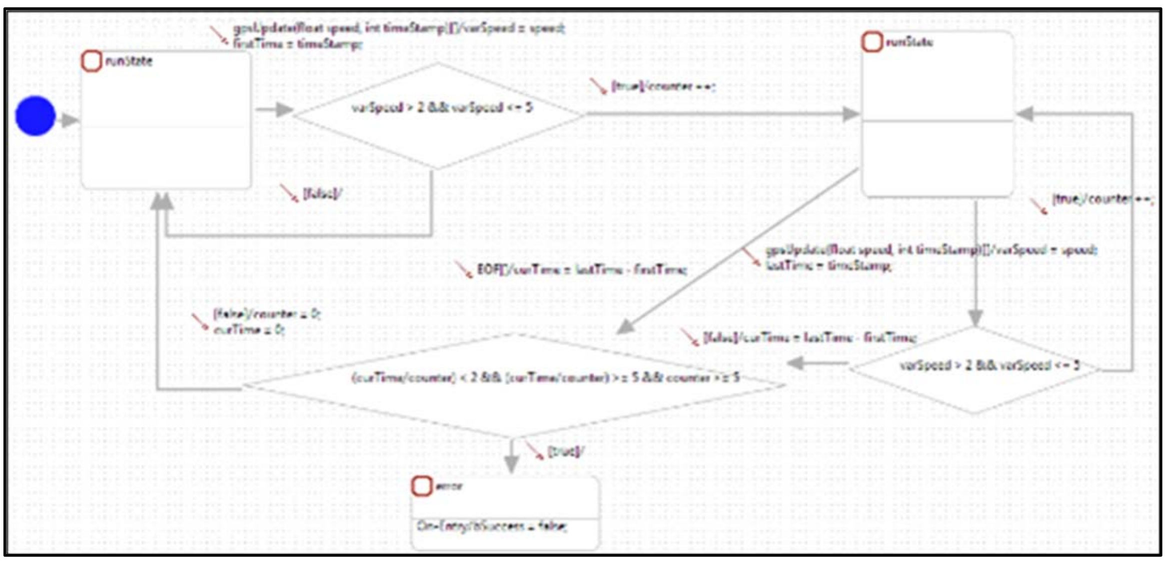

Figure 8. Statechart Assertion for Speeds Between 2 and 5 Meters per Second

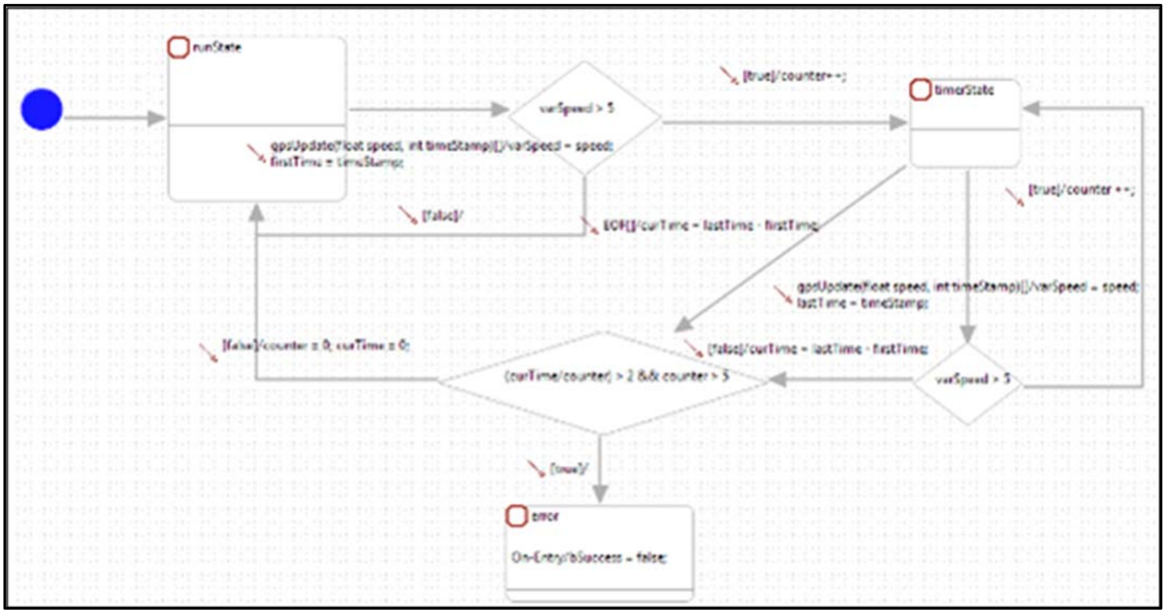

Figure 9. Statechart Assertion for Speeds Greater Than 5 Meters per Second

Figure 10 shows the statechart assertion for the requirement that a log file can only be transmitted when the device is connected to a Wi-Fi access point. Note that this statechart assertion only covers the requirement that a transmission cannot start when not connected to Wi-Fi, but does not capture the requirements that log files cannot be transmitted within an hour of each other, nor does it cover what needs to be done when the Wi-Fi connection is lost during a transmission. We chose to capture the latter with three other statechart assertions (Figures 11, 12, and 13), thus simplifying the complexity of each statechart assertion.

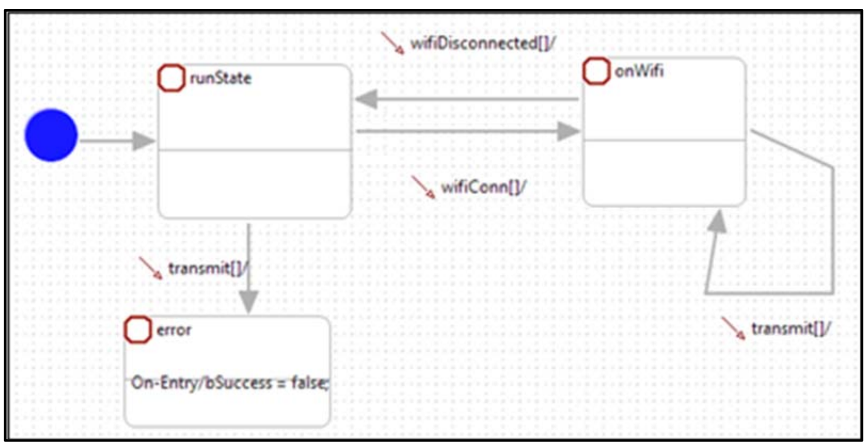

Figure 10. Statechart Assertion for Wi-Fi–Only Transmission

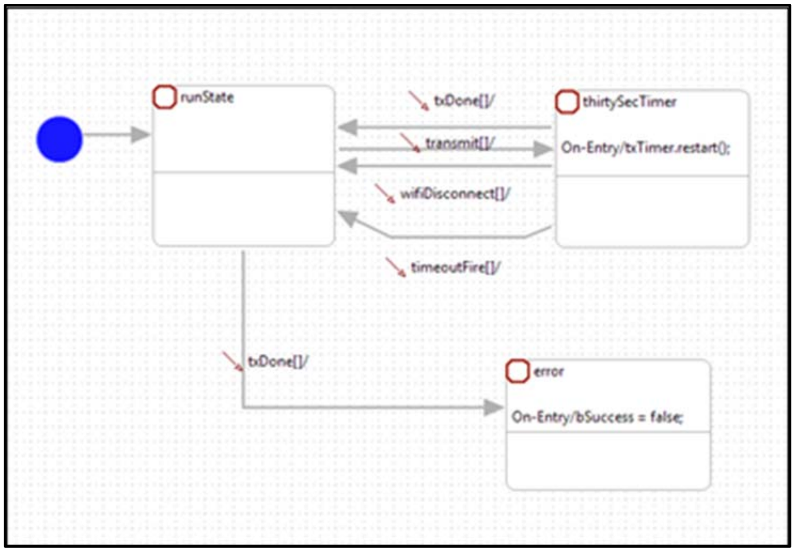

Figure 11. Statechart Assertion Limiting Log File Transmission Time to 30 Seconds

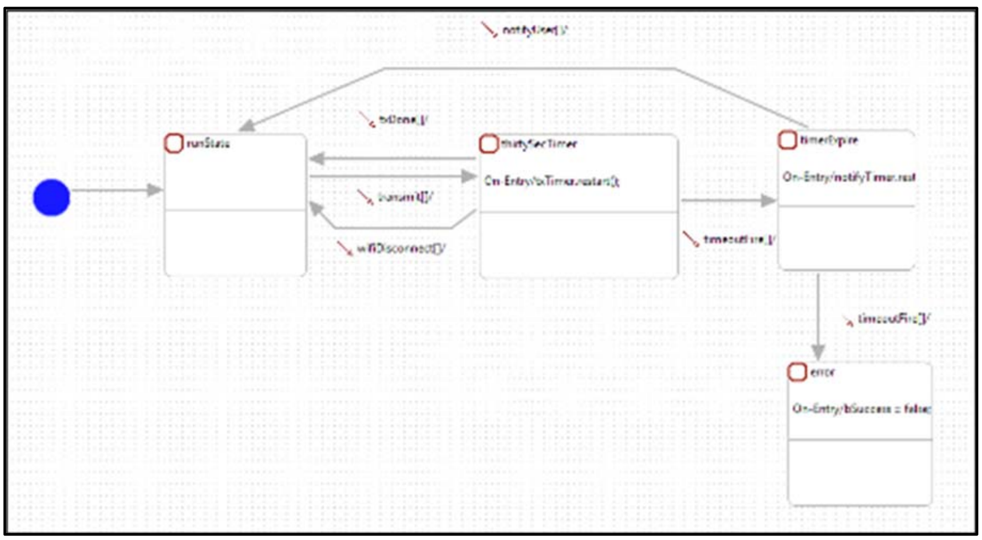

Figure 12. Five Seconds to Notify User of Transmission Failure

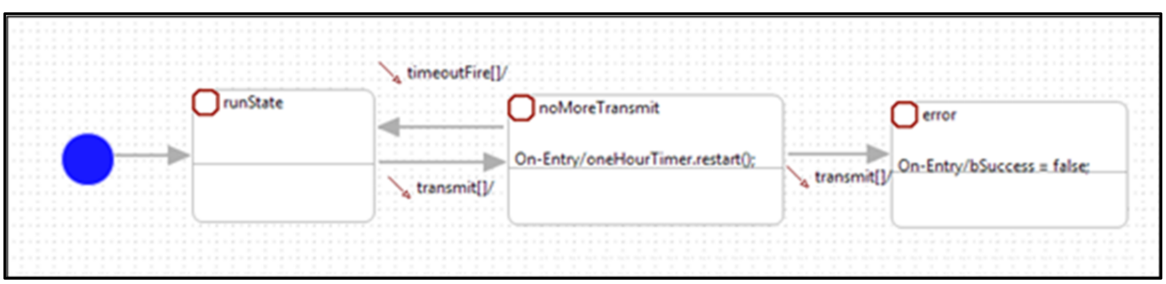

Figure 13. One-Hour Time Out Between Successive Log File Transmissions

We tested each of the above statecharts with different scenarios to ensure that they correctly capture the intent of the natural language requirements.

Log File Preprocessing and Runtime Verification

The GPS application generates log files with the data format shown in Figure 14, which is different from those required by StateRover, like those shown in Figure 15.

```
WIFI_CONN @ 11/30/2012 01:07:44 PM
WIFI_DISCONNECT @ 11/30/2012 01:07:45 PM
```

Figure 14. GPS Application Generated Data Format

```
<event>
<sig><![CDATA[wifiConn]]></sig>
<time lang="c" unit="sec" val="1354309664" />
</event>
<event>
<sig><![CDATA[wifiDisconn]]></sig>
<time lang="c" unit="sec" val="1354309665" />
</event>
```

Figure 15. StateRover Required Log File Format

In order to test the log file produced by the GPS application against the statechart assertions, we need to convert the original log into a log that can be read by the StateRover tool. We developed a Python script to convert the application log file into what we shall call a StateRover log file. Using StateRover's log file–to–JUnit converter, the StateRover log file was imported into the off-line verification environment and converted into an equivalent JUnit Java class. This class contained the log file–based verification test for the statechart assertions. Using StateRover's namespace mapping tool, we created a namespace mapping that linked the JUnit Java class's name space (events as defined in the log files) to the assertion repository's namespace (events of the statechart assertions). The StateRover's namespace mapping in Figure 16 depicts on the left-side tree (denoted the source tree) events taken from a log file and, on the right-side tree (denoted the target tree), events from all assertions in the assertion repository. Connections between the source and the target trees can be done manually using the user interface, or automatically using a built-in matching algorithm.

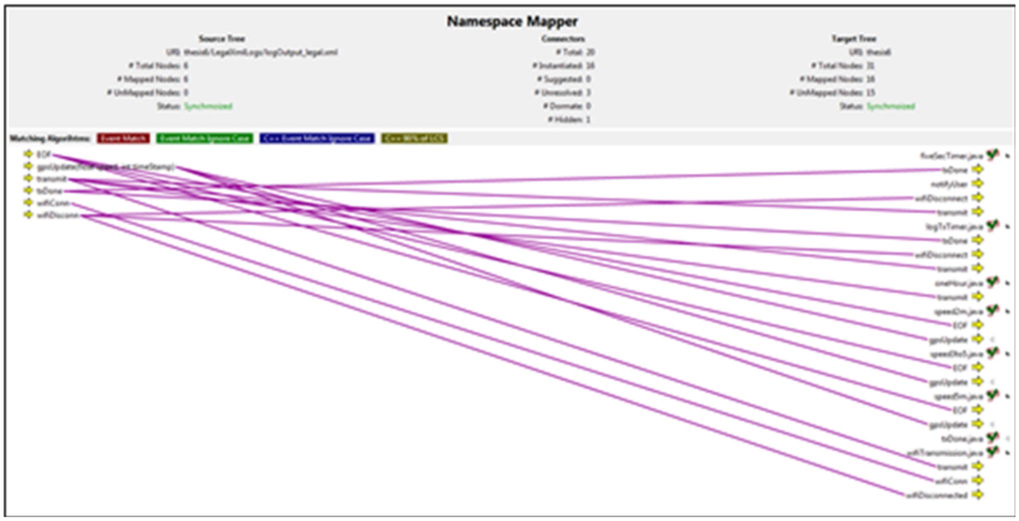

Figure 16. Namespace Mapping for Runtime Verification

Once this is complete, the test can be run by pressing the Run button in the toolbar. Figure 17 shows the desired result after testing one or more statechart assertions. If an assertion failure exists (i.e., a *bSuccess* variable in one of the assertions was set to false), the statechart assertion where it occurs will be listed on the left side under the header Statechart Assertion Failures.

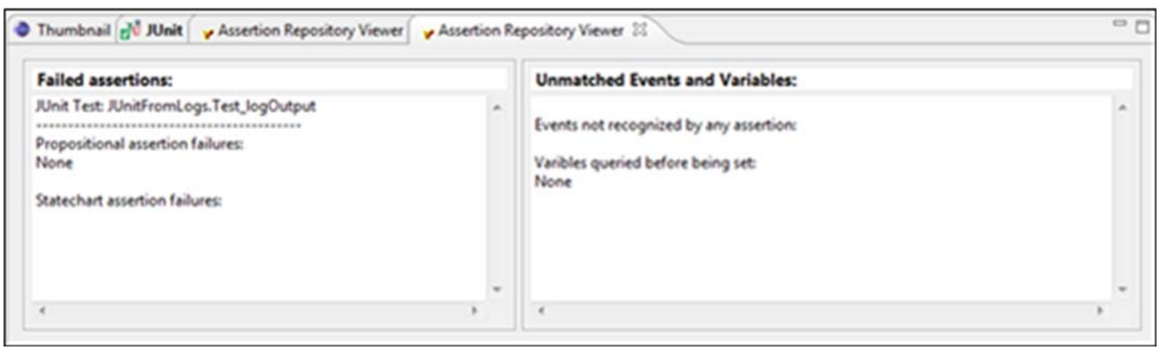

Figure 17. Test Result With Zero Failure

To validate the correct operation of the statechart assertions, we manually generated some log files containing errors. The log file in Figure 18 is an example snippet of such a log file.

```
1.0959 mps @ 11/30/2012 12:11:20 AM
1.3764 mps @ 11/30/2012 12:11:21 AM
0.9190 mps @ 11/30/2012 12:11:22 AM
0.7197 mps @ 11/30/2012 12:11:23 AM
WIFI_CONN @ 11/30/2012 12:11:23 AM
TX_START @ 11/30/2012 12:11:23 AM
1.9180 mps @ 11/30/2012 12:11:24 AM
0.5781 mps @ 11/30/2012 12:11:25 AM
0.3186 mps @ 11/30/2012 12:11:26 AM
0.7450 mps @ 11/30/2012 12:11:27 AM
0.1642 mps @ 11/30/2012 12:11:28 AM
0.7080 mps @ 11/30/2012 12:11:29 AM
1.7338 mps @ 11/30/2012 12:11:30 AM
WIFI_DISCONNECT @ 11/30/2012 12:11:30 AM
1.3015 mps @ 11/30/2012 12:11:31 AM
1.5235 mps @ 11/30/2012 12:11:32 AM
WIFI_CONN @ 11/30/2012 12:11:32 AM
0.8866 mps @ 11/30/2012 12:11:33 AM
1.4841 mps @ 11/30/2012 12:11:34 AM
TX_DONE @ 11/30/2012 12:11:34 AM
3.0644 mps @ 11/30/2012 12:11:35 AM
4.0769 mps @ 11/30/2012 12:11:35 AM
3.2224 mps @ 11/30/2012 12:11:36 AM
3.5195 mps @ 11/30/2012 12:11:36 AM
2.0872 mps @ 11/30/2012 12:11:37 AM
```

Figure 18. Sample Log File Containing Erroneous Events

Failed assertions:

JUnit Test: JUnitFromLogs.Test_logOutput

Propositional assertion failures:
None

Statechart assertion failures:
class assertionrepository.lessThan2mps
class assertionrepository.logTxTimer

Figure 19. Failures After Using the Log File

Conclusion

This paper presented a method for performing V&V on a mobile application using statechart assertion and log file–based runtime verification. The environment that the DoD frequently operates in is abnormal, to say the least, and is tough to emulate when attempting to perform V&V in a lab environment. It is important that an application is evaluated in the environment in which it is expected to operate, especially since the programmers are probably unfamiliar with that environment. Log files provide direct insight into the operation of the application, and when used in the expected environment, can ensure a thorough and valid set of V&V tests. Combining the use of application log files and statechart assertions allows testers to evaluate the behavior of an application as it pertains to its adherence to the stated requirements. Statechart assertions provide a mechanism to represent application requirements in an easy-to-follow diagram that will be used by StateRover to automatically produce executable evaluators to evaluate the application log

files. The modeling of the requirements independent of the implementation allows for multiple applications to be evaluated against the same set of requirements.

We demonstrated the method with a case study involving the V&V of a GPS mobile app. There are two different services one can use to get the user's current location: the standard location service and the significant-change location service. The standard location service is a configurable, general-purpose solution and is supported in all versions of iOS. The significant-change location service offers a low-power location service that is available only in iOS 4.0 and later, and that can also wake up an app that is suspended. Initially in our case study, we attempted to use the significant-change location service to generate the log file, but this resulted in failure of the statechart assertions for the speed-based GPS update requirements. After switching to the standard location service with highest accuracy to generate the GPS updates, we were able to produce a new log file that satisfies the statechart assertions. Note that it would be very labor intensive and difficult to manually determine if the new log file meets the requirements any better than the previous version. The StateRover's log file–to–JUnit converter and the namespace mapping tool significantly ease the task of the checking of test results; we can quickly see that the new log file (and hence the new implementation) does indeed meet the requirements, once we have imported the log file into StateRover. The methods for testing mobile apps, as discussed in The V&V of Mobile Apps in this paper, all require the manual evaluation of test results. The method put forth in this paper not only automates the checking of test results, it also allows testing of the application in the expected environment of operation. The case study provides a non-trivial example of how the use of log files and statechart assertions provide a significant improvement in the V&V process of applications.

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